Does improving the building fabric increase the risk of overheating in mid-terrace dwellings in the UK?

Fosas De Pando, Daniel

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Does improving the building fabric increase the risk of overheating in mid-terrace dwellings in the UK?

Student: Daniel Fosas de Pando
Student Number: 149387868

Supervisors:
Dr Sukumar Natarajan
Dr Alfonso Pablo Ramallo-González

Department of Architecture and Civil Engineering
The University of Bath

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Abstract

In response to the human-induced climate change, the building sector has been experiencing a deep transformation to deliver low carbon dwellings. According to emissions shares, these have mainly focused on cutting down the heating demand in northern countries by increasing the insulation and the airtightness. At the same time, the latest projections show not only that the Earth is warming but also that extreme events will be more frequent and severe, for which raises in morbidity and mortality are expected. Consequently, research and governments have considered fundamental the evaluation of current practices to ensure adequate resilience for these scenarios. A clear concern arises: do the strategies that lower heating demand increase the risk of overheating? The answer is not clear. Advances in the field have identified most influential parameters, but opinions are divided regarding the performance of building fabric.

To overcome the limitations identified, this project has integrated under the same study a wide range of constructions designed to meet 1995 and 2006 Building Regulations and FEES and PH standards. In addition, it has encompassed different locations, thermal mass, glazing ratios, shading strategies, occupancy profiles, infiltration levels, availability of purge ventilation and orientations, resulting in a total of 13 824 simulations. Such approach has two main problems: simulations aimed at the study of overheating should provide accurate temperature predictions and different standards entail different conditions. The first was addressed through the validation of the model based on a real, highly insulated mid-terrace, the most common type of dwelling that overheats. The second was solved through parametric building simulation. The proposed method has been able to contextualize different cases according to each construction standard, ensuring that simulations remained relevant.

Results show that improved building fabric achieves lower overheating risk as long as purge ventilation is available. When it is not, leakier and less insulated dwellings perform better given that external temperatures in the UK are generally below the maximum comfort temperature. Yet, this situation features a risk unlikely to be stand in reality. The tests conducted for the climate change projection in London 2080 stress the benefits of greater insulation and airtightness following the rise of the external temperatures, achieving significantly less duration and severity of discomfort. In addition, it is demonstrated that current overheating criteria can depict different trends, making them potentially unsuitable for research. Finally, the evaluation of annual energy demand for space heating and cooling shows that improvements in the first do not translate in increases of the second for the majority of cases, situation further corroborated for the climate change projection considered.

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Contents

Abbreviations

ACDD Adaptive Comfort Degree-Days.

ACM Adaptive Comfort Model.

CDD Cooling Degree-Days.

CDH Cooling Degree-Hours.

CI Bayesian Credible Interval.

CREW Community Resilience to Extreme Weather.

CSH Code for Sustainable Homes.

DHW Domestic Hot Water.

DSY Design Summer Year.

E+ EnergyPlus.

FEES Fabric Energy Efficiency Standard.

GHG Greenhouse Gases.

HDD Heating Degree-Days.

HDH Heating Degree-Hours.

HR Heat Recovery.

IDD EnergyPlus Data Dictionary File.

IDF EnergyPlus Input File.

MIDAS Met Office Integrated Data Archive System.

MV Mechanical Ventilation.

PH Passivhaus.

PHPP Passivhaus Planning Package.

PMV Predicted Mean Vote.

PPD Predicted Percentage Dissatisfied.

SAP Standard Assessment Procedure.

TM Thermal Mass.

TRY Test Reference Year.

UK United Kingdom.

WGBT Wet bulb globe temperature.

Note: Cited authors' abbreviations are shown together with their corresponding bibliography entry.

Nomenclature

Nomenclature

Term	**Description**	**Units**
A	Area	m^2
C_D	Discharge coefficient	—
C_s	Coefficient for stack-induced infiltration	$(\mathrm{Pa/K})^{\mathrm{n}}$
$C_{w,vent}$	Opening effectiveness	—
C_w	Coefficient for wind-induced infiltration	$(\mathrm{Pa\,s^2/m^2})^{\mathrm{n}}$
$F_{Schedule}$	E+ fraction schedule (0–1)	—
K_m	Heat capacity per area of element	$\mathrm{kJ\,m^{-2}\,K^{-1}}$
L	Latent heat gain	W
M	Metabolic Rate	W or *met*
Q_s	Volumetric air flow rate due to stack effect	$\mathrm{m^3\,s^{-1}}$
Q_w	Volumetric air flow driven by wind	$\mathrm{m^3\,s^{-1}}$
S	Sensible heat gain	W
T	Temperature	°C or K
V	Volume	m^3
ΔH_{NPL}	Height from midpoint of lower opening to the neutral pressure level	m
$\dot{V}_{50}$	Flow rate at 50Pa	$\mathrm{m^3\,h^{-1}}$ or $\mathrm{m^3\,s^{-1}}$
λ	Conductivity	$\mathrm{W\,m^{-1}\,K^{-1}}$
μ	Mean	*as indicated*
U-value	Thermal transmittance	$\mathrm{W\,m^{-2}\,K^{-1}}$
g-value	Solar thermal transmittance through glazing	—
ρ	Density	$\mathrm{kg\,m^{-3}}$
σ	Standard deviation	*as indicated*
EA	Effective angle (north–surface normal)	°
c	Flow coefficient	$\mathrm{m^3\,s^{-1}\,Pa^{-n}}$
c_p	Specific heat capacity	$\mathrm{J\,kg^{-1}\,K^{-1}}$
d	Thickness	*as indicated*
g	Gravity	$\mathrm{m\,s^{-2}}$
n_{50}	Air changes at 50Pa	*ach*
p	Person	p
q_{50}	Air permeability at 50Pa	$\mathrm{m^3\,h^{-1}\,m^{-2}}$
s	Shelter factor	$(\mathrm{Pa\,s^2/m^2})^{\mathrm{n}}$
v_{dir}	Wind direction	°
v_w	Wind speed	$\mathrm{m\,s^{-1}}$

Term	Description	Units
TMP	Thermal Mass Parameter	$kJ\,m^{-2}\,K^{-1}$

Subscripts and superscripts

Term	Description
n	flow exponent
air	air
cm,max	comfort, maximum
cm,min	comfort, minimum
db	dry bulb
om	monthly mean
o	operative
$real$	real value (as measured by a sensor)
rm	running mean
r	mean radiant
sim	simulated
$ventilation$	temperature that triggers ventilation
$zone$	zone

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CHAPTER 1

Introduction

1.1 Background

Over the last decades, there has been an increasing body of evidence that has correlated human activities as the drivers of current climate change due to the release of an unsustainable amount of Greenhouse Gases (GHG) (IPCC 2015). Among these, the building sector accounts for a notorious fraction, especially in the UK, where it has been responsible for about 45% of the GHG emissions. Hence, numerous initiatives have been adopted to lower and optimize the energy consumption, crucial if it is considered that the UK has committed to reduce overall emissions 80% from 1990 levels by 2050 to slow down the climate change. At the same time, the energy consumption of this sector has increased 2% when compared to 1995, reaching 41% of the share (European Commission 2014). According to its breakdown, there has been a special interest in improving the building fabric to lower the heating demand as it represents about 47% of their GHG and about 16% of UK's total emissions (figures based on Palmer and Cooper (2013) energy consumption and carbon intensity of Energy Saving Trust (2014)).

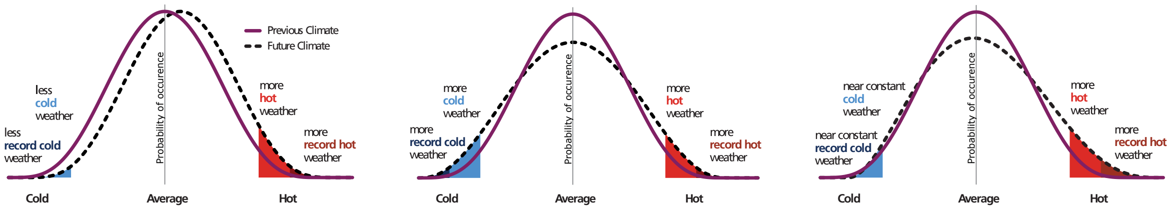
As a result, the environmental demands aligned with those that arose from the oil crises, settling down the paths for greater insulation and airtightness. This has been directly translated into building regulations, where, in the last four decades, values have been increasingly strict. New dwellings are required nowadays to achieve transmittances three times better than in 1970 (ODPM 2013a). Airtightness, following this trend much later, is also expected to deliver between half to a quarter the air leakage (ODPM 2013b). In addition, the uptake of voluntary standards has lowered these targets further. The Fabric Energy Efficiency Standard (FEES) aims to reduce heat loss through the fabric about half of what currents regulations require, whereas Passivhaus (PH) is based on even more ambitious targets. Here, the improvements they establish over the building fabric have to deliver, among other requirements, a heating energy demand up to $15\,\mathrm{kWh/m^2/year}$, 38% of what is expected from FEES. Overall, these trends have been changing the way construction is understood as meeting these requirements entail deep shifts from traditional practices. Although necessary, these measures are not sufficient for this sector. Buildings have a significant lifespan, being currently designed for at least fifty years. In fact, 18% of the current dwelling stock was built before 1918, 33% in 1918–1964, same as for the period of 1965–1990. Only 16% has been built ever since climate change was a public concern (fig. 1.1). Consequently, the government has been implementing numerous initiatives, to promote higher insulation for these as well. Since 2009, it can be considered that there are no houses without some sort of insulation but still more than two-thirds lack of the levels retrofit practices could have delivered then (Palmer and Cooper 2013).

Figure 1.1: "Heat Loss Parameter by dwelling age (2011)" (Adapted from Palmer and Cooper (2013, Graph 5h))

At the same time, the climate keeps changing. The IPCC has confirmed in their latest reports a constant increase in the Earth's surface temperature over the last three decades, reaching unprecedented values. In addition to all indicators, this points to *likely*[1] raises of 1 to 2 °C on the *global mean*, expecting higher ones for urban locations (IPCC 2014). In fact, these are only when considering that substantial changes at technological, economic and governmental levels are to be met. The raises would lay in the range of 2.5 to 3 °C if measures were adopted at slower pace. Anyhow, variations in these ways alter the distribution of temperatures, resulting in significant changes in the lower and upper ends: future climate is depicted with a significant increase of extreme weather effects, in special those associated with hotter ones (fig. 1.2). In a special report devoted to this issue, it has been observed with *medium confidence* changes towards higher length of these events being *very likely* the hike in frequency (IPCC 2012). Furthermore, it is *virtually certain* that all of these will be surpassed, resulting in more severe and longer events.

Besides the harmful effects on the environment, hot spells and heatwaves are known to increase morbidity and mortality because, beyond a certain threshold, the body is no longer able to maintain the core temperature in suitable levels. During the European heatwave of 2003 an increment of 70 000 deaths were recorded, most of which were elderly (Robine et al. 2008). Numerous studies have been looking at such experiences in order to understand and prevent these rates, where they recognized the fundamental role buildings have to alter the final indoor temperature and thus, promoting higher or lower risks. This raises the fundamental question of whether the measures focused on achieving higher temperatures during cold season to cut down the heating demand result in higher overheating risk during the hot ones or not.

[1] The terminology established by the IPCC to express the confidence of observed and projected changes has been maintained with its original meaning.



(a) "Shifted Mean" (b) "Increased Variability" (c) "Changed shape"

Figure 1.2: "The effect of changes in temperature distribution on extremes" (Adapted from IPCC (2012, Figure 1-2))

Research has proven that the pressure for lower energy consumption and carbon emissions can arise unexpected consequences, which, in addition to the problems they create, hinder the performance of policies and strategies aimed at reducing GHG emissions. Among these, one of the majors concerns has been the resilience under a changing climate, topic under which overheating plays an important role (Mylona and Davies 2015). Especially since 2003, there has been an increasing amount of research devoted to see if improved building fabric exacerbates temperatures during summertime in heating dominated countries. During the mentioned heatwave, it was found that higher internal temperatures were recorded in rooms without insulation whereas, in the same year, the study by Orme et al. clearly linked higher overheating risk with increases of insulation (Dengel and Swainson 2012). However, both conclusions are not comparable since they are referred to very different contexts: Parisian dwellings during the heatwave and building simulations in the UK assessing the performance of a house built to 2002 standards versus a proposed update more stringent with U-values. The projections of the UKCIP02 allowed, at about the same time, insights of future performance, in which CIBSE based the TM36 "Climate change and the indoor environment: impacts and adaptation" (2005). The study concluded that the performance of increased insulation and reduced air leakage is two-fold, being possible to rise and lower overheating risk depending on the hourly balance (more on this on chapter 2).

Nonetheless, the main components are clear —external and internal gains together with ventilation—, but there has been much debate about their interactions, reason why there has been a tendency to include an increasing number of parameters that affect these over subsequent studies. In addition, it has been pointed out that their performance is sensible to the locations under study as well (J. Taylor et al. 2014). Currently, the role of improved building fabric remains unclear, having been proven both possibilities, although it has to be considered that each of the studies differ from the others: the particular research questions, scopes, methods and parameters under study do not make them comparable (chapter 2).

As a result, additional studies have been requested. The government summarized the key areas of future research regarding overheating and climate change, which includes specifically the role of insulation and the quantification of the potential trade-offs in energy demand and are still unanswered (DCLG 2012a; DCLG 2012b). More recently, it has been asked for more studies to clarify what are the benefits and risks of current standards and policies, together with the overheating criteria available (Mylona and Davies 2015; Gupta and Kapsali 2015). Finally, the Zero Carbon Hub is carrying an ambitious project not only to clarify these issues, but also to develop a methodology able to quantify it consistently. Due to 2016, they are currently requesting and collecting studies to inform updates to the Standard Assessment Procedure (SAP) and to advise the UK government and the building sector (ZCH 2015c).

CHAPTER 2

Literature review

To approach the relationship of overheating and improved building fabric, the literature review has been organised around two key issues: definitions of overheating and overheating in dwellings. On the first, the main considerations of what is overheating are discussed together with the analysis of how these are translated into standards and reference criteria. Building on that, the second reviews the studies that have looked at overheating in dwellings which, according to the complexity of this topic, has been organised into four main areas, namely parameters that affect overheating, delimitation of influential ones, field studies and annual energy balance.

2.1 Definitions of overheating

There is not yet a widely accepted definition of what is overheating in buildings. Intuitively, it can be said that 'overheating is the raising of a certain temperature beyond a certain threshold for a certain period of time', where further specification is subject to discussion. Thus, overheating is better expressed as a risk because temperatures depend on the energy exchange in constantly varying circumstances[1]. According to what is assessed, overheating relates to health risks, comfort and productivity of which only the first two are relevant for dwellings (ZCH 2015a). Health risks express the consequences of the body's failure to control its internal temperature (e.g. heat stroke) (HSE 2013) whereas thermal comfort is defined as "that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (ANSI/ASHRAE 2013, p. 3).

The knowledge about overheating and health risks is twofold. On the one hand, the relationship on healthy adults is well defined and understood (Lundgren 2014). Here, an implementation of the Wet bulb globe temperature (WGBT) defines the threshold for the 'heat stress index', a metric that integrates all parameters involved. The ISO-7243:1989 (BSI 1994) establishes the reference, which remains essentially the same in the upcoming revision, recently opened for consultation (BSI 2015). On the other hand, the relationship on vulnerable groups —namely children, elderly and sick people— is not that well developed. Despite early warnings of the IPCC (1990), it has not been until more recent experiences of heatwaves (e.g. that of France in 2003) and extreme weather events projections that an increasing amount of

[1] For convenience, literature often expresses 'overheating risk' as 'overheating', practice followed here.

efforts have focused on this area (Dengel and Swainson 2012; IPCC 2012). However, there is not an international framework that clarifies and quantifies these risks in relation to indoor air temperature, only definitions of what is a heatwave and which actions should be taken under such events (ZCH 2015b).

Unlike with health risks, thermal comfort features numerous schemes to assess overheating. Here, it can be reworded as 'an unacceptable level of dissatisfaction due to excessive heat' according to the two main ways of understanding thermal comfort: Fanger's Predicted Mean Vote (PMV) - Predicted Percentage Dissatisfied (PPD) and Adaptive Comfort Models (ACMs). Thus, they can entail explicit temperature thresholds; notwithstanding it is still a *risk* —even more so as comfort translates to a PPD—. Given the technical possibilities, it is only relevant to talk about overheating where the building 'can be expected to perform adequately without air conditioning' —i.e. free running buildings in certain climates—, although it has also been used to characterise energy demand or the potential effects of climate change in warmer regions (see section 2.2.4). However, the limits of this expectation, duration and severity, do not translate directly from the PMV-PPD or the ACMs, having being proposed a number of overheating criteria based on them. Since known health risk thresholds (i.e. healthy adults) cannot be reached in these circumstances, the following sections focus exclusively on the thermal comfort perspective.

2.1.1 Comfort benchmarks based on PMV-PPD

Two main standards implement the PMV-PPD model, the ANSI/ASHRAE-55 2013 and the EN-7730 (BSI 2005). The only noteworthy difference is that the American regards as acceptable a PPD up to 10%, whereas the European proposes categories based on degrees of satisfaction up to a PPD of 15%. Knowing the typical situations in dwellings, an operative temperature and its dispersion can be worked out (table 2.1). From this, studies have consecutively supported the raising of temperatures to set limits to discomfort, where the main references are CIBSE, Passivhaus and the EN-15251.

Table 2.1: "Customary" summer conditions (Reproduced from CIBSE (2015, Table 1.5))

Room	T_o [°C]	Activity [*met*]	Clothing [*clo*]
Bathrooms	23–25	—	—
Bedrooms	23–25	0.9	1.2
Hall/stairs/landings	21–25	—	—
Kitchen	21–25	1.5	0.5
Living rooms	23–25	1.1	0.6
Toilets	21–25	—	—

CIBSE's TM-36 provides an *illustrative* fixed threshold for free-running buildings based on PMV-PPD. They argued that an assessment using ACM —ASHRAE's model was included in the 55-2004 Standard a year ago— "results can be difficult to interpret" (without further explanations) (CIBSE 2005, p. 9). The criterions rely in setting a 'warm' and 'hot' limits —PMVs +2 and +3, respectively— by adapting clothing and PPD. If 'hot' conditions are met for more than 1% of the occupied time the building is said to overheat (reasons why 1% not given; remarkably the cited 5% for 'warm' is deprecated). Severity is overlooked. The limits for dwellings are derived from research and experiences in offices and schools, as usual. Although precise values for clothing and metabolic activities are not explicit, the operative temperature limit in living areas is established to 25 (‘warm’, PPD< 10%) and 28 °C (‘hot’, PPD< 20%) (table 2.2). Thresholds for bedrooms are adapted to 21 and 25 °C, respectively, according to what they considered occupant’s expectations. Still, Humphreys’ findings support these values (fig. 2.1), although PMV-PPD application would result in 26–27 °C due to the lower metabolic activity provided suitable bedding (0.9*met*, 0.5–0.7*clo*). For predictions, the 1% criterion implies the use of Design Summer Years (DSYs) (i.e. third Apr–Sep hottest year on average in 1983–2002) rather than Test Reference Years (TRYs) (i.e. typical year with 1976–1990 average months) so the risk is explicitely taken into account by maximizing it within reasonable limits.

Table 2.2: TM-36 overheating criteria (Adapted from CIBSE (2005, Table 3.1))

Room	‘Warm’ threshold [°C]	‘Hot’ threshold [°C]
Living areas	25	28
Bedrooms	21	25

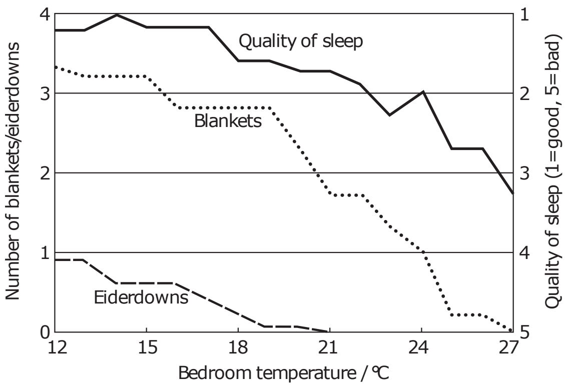


Figure 2.1: “Bedclothing and sleep quality” in the UK (Hymphreys (1979) reproduced by CIBSE (2015, Figure 1.6))

Built on the same grounds, Passivhaus (PI 2014) sets the *default* limit to T_o= 25 °C (customizable) for a duration up to 10% (compulsory) of the occupied time, implementing findings from Kolmetz (1996)[2]. Hence, it is stricter for the temperature but more relaxed for the deviation as severity is also overlooked.

The EN-15251 (BSI 2007) proposes *how to characterise* comfort performance, applicable to both PMV-PPD and ACM, that sets a time limit for discomfort. The length of deviation is set, as *an example*, to 3 or 5% and has to be met *simultaneously* for the occupied periods at year, month, week and day level. Then, it offers three alternatives to compute occupied hours in discomfort. The first one is a count of the time when comfort is exceeded (as seen before). The second is a degree-hours approach like in Heating Degree-Days (HDD)-Cooling Degree-Days (CDD) according to ΔT_o over the limit. Reasons why they use a metric thought for *energy demand* to appraise *comfort* remains unknown. The third one is a PPD-weighted metric, similar to the previous but weighting ΔPPD over the limit, more sensible as this parameter does assess comfort. They point out that PPD-weighted yields greater hours, not explaining the causes. Here, they are attributed to the non-linearity of PPD(ΔT_o), true in every thermal comfort model. In fact, it can be seen that each method gives higher results than the previous, potentially discouraging the use of the last two. The category of the builiding is the highest

[2]Kolmetz’s research could not be discussed in the time frame of the Dissertation as the only copies available, in German, are held at the Technical University of Munich.

one that is satisfied in 95% of its spaces. However, this can be misleading as the period and counting method are voluntary, as noted by (Nicol and Wilson 2011).

2.1.2 Comfort benchmarks based on ACMs

Likewise, the ANSI/ASHRAE (2013) and the EN-15251 (BSI 2007) implement ACMs. The different databases from which they were derived —RP-884 'worldwide' (de Dear et al. 1997) and SCATs 'Europe' (McCartney and Fergus Nicol 2002), respectively—, the methods and the assumptions involved do not make them truly comparable (Nicol and Humphreys 2010; de Dear et al. 2013). As explained by de Dear et al. (1997), adaptations under PMV-PPD only accounted for about 50% of comfort experienced under ACMs, making them more appropriate for free-running buildings. The American offers two limits around comfort that result in 80 and 90% acceptability (general and higher comfort, respectively). The European gives three qualitative levels —I/II/III— whose first two coincide in their intended use definition on each standard —80% $\approx II$ and 90% $\approx I$—. Quantitatively, PPD definitions were traced back to ACMs research (table 2.3). Reasons for the mismatch in the PPD definition could not be found in the literature reviewed and are outside the scope of this dissertation, but further illustrates why they are not comparable (apparently they would yield different PPD but care must be taken to see what was specifically considered (Nicol (pers.comm.) 16 July 2015). Only the EN-15251 suggests how to quantify the performance of the building regarding discomfort, as explained in section 2.1.1. Interestingly, the concept of Adaptive Comfort Degree-Days (ACDD) for energy demand was not defined nor validated until later on by McGilligan et al. (2011).

Table 2.3: Comparison of ANSI-55 and EN-15251 ACMs

Standard	Category	ΔT_o [K] (T_{rm}-based)	ΔT_o [K] (T_{om}-based)	PPD (PMV)	Cualitative equivalent
EN-15251[a]	I	±2	—	16% (±1.00)[b]	ANSI-55 90%
	II	±3	—	23% (±1.00)[b]	ANSI-55 80%
ANSI-55[c]	90%	—	±2.5	10% (±0.50)[d]	EN-15251 Category I
	80%	—	±3.5	20% (±0.85)[d]	EN-15251 Category II

[a] BSI (2007) [b] Nicol and Humphreys (2007) [c] ANSI/ASHRAE (2013)
[d] de Dear et al. (1997)

The TM-52 (CIBSE 2013), chaired by Nicol, recommends the European ACM to appraise overheating in free-running buildings, as indicated by research (no more interpretation issues). The background summarises the state-of-the-art of the model and establishes a limit to overheating inspired in the EN-15251 but based on three criterions: if any two are exceeded the building is said to overheat. The first one establishes a limit of 3% on the May-September occupied hours for $\Delta T_o \geq 1\,\mathrm{K}$ (which was an *example* in the EN-15251). The second uses the hour-degree method limited to six in any one day. The reasons given six is that it "is an initial assessment of what constitutes an acceptable limit of overheating" (CIBSE 2013,

p. 14). The third one is novel and establishes $\Delta T_o \leq 4\,\mathrm{K}$ to account for severity, which maintains the PPD under $\approx 35\%$. This way, TM-52 catches up with previous critics (e.g. Nicol et al. (2012)). Additionally, it mentions that ACMs should be suitable for dwellings as adaptability premises are truer, despite being derived from offices. Moreover, it reminds that EN-15251 Category I could be used if tighter control is deemed necessary. ACMs' suitability for bedrooms is not discussed, where it might not be applicable as they were devised for a range of 1–1.3*met* (offices) and sleeping is 0.9. The Guide A (CIBSE 2015) does mention them, setting comfort up to 24 °C and an absolute limit of 26 °C (based on Humphrey (fig. 2.1)). Again, remains unknown why the PPD-weighting was disregarded whereas it is understood that the simultaneity criteria of the EN-15251 was indirectly approached with three criterions.

2.2 Overheating in dwellings

Because overheating is the consequence of heat build-up inside the building, numerous publications have enumerated the causes behind it, where the most comprehensive reviews are still those by CIBSE (2010) and Dengel and Swainson (2012). Essentially, these are descriptions of all the energy transferences that can take place in a building. Put simply, external and internal sources of heat drive these transferences, with the boundary between the two hindering or promoting them. Thus, overheating —given a definition— is characterized by the interaction of these three components where the relationships of interest are those that maintain thermal comfort under the upper limit in a free-running building. However, design influence over gains is usually deemed very limited. Likewise, external ones are down to the weather, which, in addition, will feature warmer scenarios as depicted by climate change projections and urban heat island studies (IPCC 2012). Additionally, internals involve occupants, being only possible to narrow down likely gains through energy efficiency measures (IEA 2015). Hence, studies have generally focused on the third component.

The definition of the boundary's fixed elements (orientation, glazing ratio, U-values, air-tightness…) determines a 'default behaviour' for the annual performance, which can be adapted through the operation, either automatically or manually, of certain elements (ventilation —openings, building services—, shading devices…). Overheating discussion arises when the 'default behaviour' promotes a lower demand in heating-dominated climates, which leads to greater insulation and airtightness as means to tightly control gains. Thus, it has been argued that this strategy can move the demand up to the extent of needing active cooling during the warmer seasons, being classified among the unintended consequences of energy efficiency measures in a warming climate (RPA 2012). On the other hand, it has also been said that they will prevent higher temperatures to get into the building, having a positive effect (CIBSE 2010). Unsurprisingly, both statements are possible depending on the combination of parameters for a given case. Hence, an increasing number of studies have been exploring *how* parameters can affect overheating risk, although their direct comparison is impossible because each one was developed with different research questions, methods and assumptions (table 2.4). Still, there are recurring aspects and findings that partially delimit the scope of interest around parameters, their ranking and how changes in the building fabric alter them.

Table 2.4: Comparative analysis of studies regarding overheating and insulation

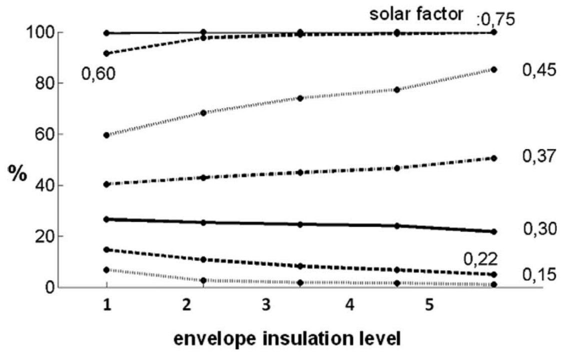
Research	**Year**	**Scope**			**Method**			**Assessment**			**Findings related to overheating and insulation**
		Building type	Location	Weather	Monitored building	Simulation	Comfort Model	Time	Severity	Energy demand	
Chvatal & Corvacho	2009	Dwellings, Offices	Portugal (3) + Italy (1) + Greece (1)	P	—	✓	A	C	✓	H+C	Higher insulation resulted in increasing or decreasing overheating, depending on solar gains.
Chvatal	2010	Commercial	Brazil (3)	P	—	✓	F	—	—	H+C	Higher insulation increased cooling energy demand for high set-points and envelopes with low solar absorption.
Porrit et al.	2011	Dwellings (various)	UK (—)	P*	—	✓	F	W	—	—	Increased insulation showed both increases and decreases in overheating, depending on case and dwelling type.
Porrit et al.	2012	Dwellings (Terrace)	UK (1) (London)	P*	—	✓	F	W	—	—	Increased insulation was beneficial to reduce overheating risk, but in certain cases internal one was not.
Mavrogianni et al.	2012	Dwellings (various)	UK (1) (London)	P+F	—	✓	*	—	✓	—	Internal solid wall insulation can potentially increase overheating under certain circumstances.
Duckworth	2013	Dwellings (various)	UK (3)	P+F	—	✓	F+A	C	—	—	Higher insulation did not necessarily meant higher overheating risk. Yet, its performance was more sensible to input conditions.
Grupta & Gregg	2013	Dwellings (various)	UK (3)	P+F	—	✓	A	C	—	—	How higher insulation affects overheating depended on the dwelling type and many other factors.
McLeod et al.	2013	Dwellings (end-terrace)	UK (1) (London)	P+F	—	✓	F	C	✓	H	PH performance mainly dependent of the solar heat gains (slightly better than FEES). Overheating begins in 2050.
Taylor et al.	2014	Dwellings (various)	UK (6)	P+F	—	✓	*	—	✓	—	Different retrofit measures yielded different overheating patterns. Overheating risk was sensitive to the location.
van Hoof et al.	2014	Dwellings (various)	Netherlands (1) de Bilt	P	—	✓	A	C+W	—	—	Higher insulation (U-value 0.20–0.15 $\mathrm{W\,m^{-2}\,K^{-1}}$) increased ≈ 8–13% overheating hours.
Mavrogianni et al.	2014	Dwellings (various)	UK (1) (London)	P	—	✓	F	C	✓	—	Occupant patterns and behaviour greatly influences overheating (assessed for retrofit packages).
Gupta et al.	2015	Dwellings (various)	UK (3)	P+F	—	✓	A	C+W	✓	H+C	Unlike heating, cooling energy consumption seem less dependent of the thermal properties of the dwelling.
Gupta & Kapsali	2015	Dwellings (various)	UK (—)	P	✓	—	F+A	C+W	✓	—	CSH Levels 4–5 houses overheated due to faulty building services, not because high insulation or thermal mass.
Makantasi & Mavrogianni	2015	Dwellings (flats)	UK (1) (London)	P+F	—	✓	F+A	C	—	H+C	Wall insulation influence on overheating trend depended on which other aspects were retrofitted.

Weather: *P*resent, *F*uture. *Comfort Model:* *A*daptive threshold (ACM), *F*ixed threshold (PMV-PPD), * Statistical description.
Time: *C*ount, *W*eighted. *Energy demand:* *H*eating, *C*ooling.

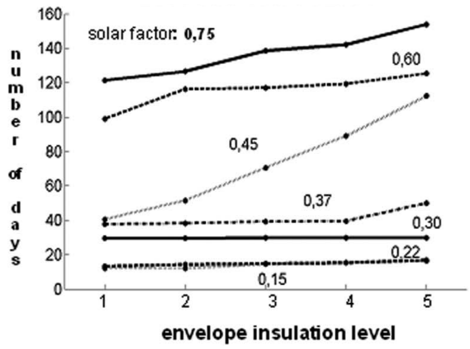
2.2.1 Parameters affecting overheating risk

From the energy transferences, it is easy to identify simple overheating situations (e.g. high solar gains), leading to sensible advices of how to avoid them (e.g. lower internal gains, increase ventilation) (RPA 2012). However, the numerous situations that can arise in practice are not, reason why a significant amount of overheating research has focused on parametric studies through building simulations.

Chvatal and Corvacho (2009) specifically studied the relationship between overheating and insulation. They altered U-values, shading and night ventilation for a free-running dwelling in various locations. The main finding was that discomfort hours trends shifted according to shading conditions in certain circumstances (fig. 2.2). Higher insulation was unfavourable for extremely high overheating cases (during 40–100% of the occupied time) whereas it was not for the more realistic subset (<40%). Generally, the shift in sign for the curves were for solar factors around 0.32–0.61, but the low purge ventilation rates considered (from 0.60ach up to 3 in certain strategies) suggest these might not be reliable in absolute terms. Yet, they show potential for normal shading situations given their range and the fact that they were modelled as constant values (windows were always shadowed the same level despite the sun's position). Remarkably, explanations for the trend shift were simply attributed to lower solar gains, not discussing what happened inside the spaces and how these related to outdoor conditions.



(a) Percentage of discomfort hours during summer



(b) Number of consecutive days of discomfort per year

Figure 2.2: Chvatal and Corvacho (2009, Figures 7 (left) and 8b (right)) extract of findings (Insulation levels (walls): 0.90–0.20 $\mathrm{W\,m^{-2}\,K^{-1}}$ (1–5, respectively))

Porritt et al. (2011; 2012) performed several studies regarding measures to lessen overheating during heatwaves as part of the Community Resilience to Extreme Weather (CREW) project. Focusing on retrofits and mid-2000 dwellings, they assessed, in addition to Chvatal and Corvacho's study, orientations, wall coats, glazing types and occupancy profiles, showing that all parameters mattered. The research concluded that the control of solar gains was the most effective measure, and that insulation was beneficial except when located in the interior. Mavrogianni et al. (2012) arrived at similar conclusions about insulation when characterizing London dwellings and retrofit measures. Moreover, Gupta and Gregg (2013) further supported these findings but stressing that overheating performance highly depends on how measures are combined.

Still, all previous studies, due to location and scope, do not achieve super insulated dwellings (e.g. most with walls around 0.40 $\mathrm{W\,m^{-2}\,K^{-1}}$). Duckworth (2013) specifically addressed the role of insulation for climate change projections in the UK, concluding that the performance of high U-values ($\approx 0.15\,\mathrm{W\,m^{-2}\,K^{-1}}$) was much more sensitive to design features, being possible to achieve either higher or lower overheating risk as a function of purge ventilation strategies: when not available higher insulation levels raises the risk, lowering it otherwise. At the same time, McLeod et al. (2013) published a study about future performance of Passivhaus and FEES dwellings, proving that the better insulation of the first outperformed the slightly lower levels of the second in their cases. In both studies, on the lines of Mavrogianni et al., variations of internal temperatures compared to the base case were around $\pm 1\,\mathrm{K}$ for most cases, making absolute conclusions potentially sensible to the overheating criteria employed. However, van Hooff et al. (2014) found exactly the opposite, concluding that a reduction of U-values from 0.20 to $0.15\,\mathrm{W\,m^{-2}\,K^{-1}}$ increased significantly overheating in their study. Explanations for this cannot be given due to large variations between them and the limited amount of information published, not knowing whether this was due to different locations, parameters, assumptions, overheating criteria or a combination of them.

In this regard, J. Taylor et al. (2014), building on Mavrogianni et al. studies, focused on the influence of different locations, obtaining significant changes in overheating patterns within the UK. Yet, performance of each measure remained qualitatively the same for most parameters (i.e. retrofitting windows decreased overheating everywhere). Additionally, the study correlated wall retrofits to internal temperature increases of 0.1–3.5 K —similar to the combined reduction due to roof and windows ones—, a much larger variation than the original $\pm 1\,\mathrm{K}$. A further publication, based on the findings from CREW, investigates how overheating changes for different occupancy patterns (pensioners, always home, and working family, away from 9 to 18h) considering different levels of engagement with the operation of windows and shading devices. Rather obvious, overheating increased significantly for the higher internal gains and reluctance to operate elements. Still, the contribution lied in quantifying the extent to which this alters overheating (more on this on section 2.2.2) and the implications this can have for people who are not able to operate the house as advised. Again, highly insulated dwellings were out of the scope of these researches.

2.2.2 Delimiting most influential parameters

Overall, findings reviewed on the previous sections show a tendency towards a holistic characterization of energy transferences, arriving to the idea that every parameter can matter. In addition, it has been stressed that combined performance is not simply the sum of individual ones (e.g. Gupta and Gregg (2013) and Makantasi and Mavrogianni (2015)). However, few studies of the literature reviewed have fully characterized the contributions of each parameter when combined between them.

J. Taylor et al. (2014) specifically focused on the relationship between overheating and the characteristics of London dwellings, finding, in general, similar trends over studies, although the importance of parameters did vary in different locations. Unfortunately, the scope of their studies did not cover their ranking because their aim was to characterize the building stock. A recent publication focused on retrofit packages performance, covering a limited number of variables and not achieving high U-values (Makantasi and Mavrogianni 2015). On the other hand, McLeod et al. performed a sensitivity analysis of thermal mass, glazing ratio, shading, airtightness and internal gains for the mentioned Passivhaus and FEES variants (fig. 2.3). They found that the most important factors were glazing ratio, followed by thermal mass, shading devices and airtightness, although this ranking has to be contextualized with the range of the variables (table 2.5). Unfortunately, ventilation was not included because it was considered out of the scope of a Passivhaus designer.

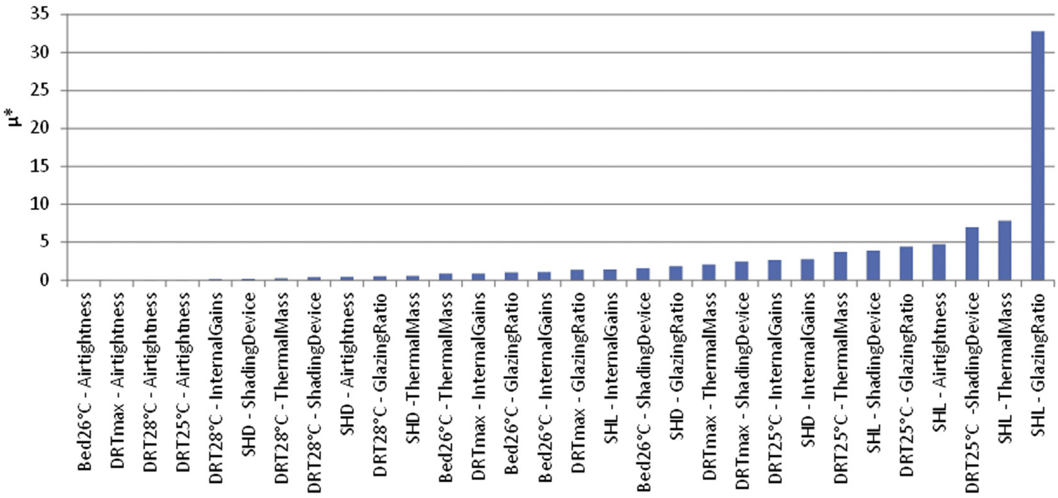


Figure 2.3: McLeod et al. (2013, Figure 12): "Ranking of output factor sensitivity – combined measures"

Table 2.5: McLeod et al. (2013, Table 3): "Sensitivity analysis parameters"

Parameter	**Distribution type**	**Min–max (or discrete values)**
Thermal mass	Discrete	Light, medium, high
Glazing ratio on south façade	Uniform	10–60%
External shading transmission factor on south façade	Uniform	0–100%
Airtightness	Uniform	0.0042–0.042ach
Internal gains (excluding occupant gains)	Discrete	0.69–2.06 W m^{-2}

2.2.3 Field studies

Despite the large casuistry studied through building simulations, it has been consistently pointed out that modern buildings overheat significantly more than older ones (DCLG 2012b; M. Taylor 2014). Pairwise comparisons with different insulations levels have not been found in the considered literature —it would be unusual to achieve this conditions in practical terms—. Yet, there have been several studies reporting the performance of Passivhaus or CSH Level 4 and 5 dwellings, for instance (Sameni et al. 2015; Gupta and Kapsali 2015). In these cases, together with the literature they review, dwellings did overheat but the causes aimed to performance gaps, not insulation itself, being common issues with building services (e.g. poor commissioning, heating during summer or gaps in pipe insulation). In addition, typologies play an important role, as is the case of the flats reviewed by Sameni et al.: both simulation and field studies have shown that flats are prone to overheat, mainly because of limited ventilation options and solar exposure (ZCH 2015c).

2.2.4 Increased insulation and annual energy demand

Although the tandem overheating and insulation originated as an unintended consequence of energy efficiency measures, fewer studies, compared to those of comfort, have included information regarding energy consumption (table 2.4). Chvatal and Corvacho (2009) appraised it for their subset of dwellings located in Lisbon, showing an overall reduction of the energy demand in every situation, being this advantage marginal if rooms are not adequately shaded. However, care must be taken because of the way shading was modelled in their study: heating demand was optimal as no shading at all was modelled in winter (optimistic). Collins et al. (2010) focused specifically on future energy consumption of dwellings in the UK, showing that heating will still be the major energy demand. Here, improved fabric ($\approx 0.25\,\mathrm{W\,m^{-2}\,K^{-1}}$) would significantly reduce the heating consumption, but not the cooling one, which achieved a performance similar to that of other fabrics considered ($\approx 0.40\,\mathrm{W\,m^{-2}\,K^{-1}}$). From this, the study concluded that the overheating performance of 'well insulated' houses was not better than the others, but this extrapolation is not necessarily right as cooling demand does not *unmistakably* translate to comfort. Gupta et al. (2015) arrived at similar conclusions regarding consumption, but in this case cooling demand was higher than anticipated. Lastly, Makantasi and Mavrogianni (2015) showed in their retrofit studies that the balance between heating and overheating was very sensitive to the specific measure implemented (e.g. fixed shading had an impact of ratio $+1 : -1.4$ while movable was $+1 : -4$ (heating:overheating)), advising all-year-round appraisals of performance.

2.2.5 Conclusions and contribution to knowledge

Most of the current knowledge related to overheating and comfort was established by 2007. Despite its appropriateness for free-running buildings, studies have generally overlooked ACM–based criteria, until it was recognised as the most suitable model to assess future performance in a warming climate and its inclusion in CIBSE's TM-52. In this regard, it has been proven that discomfort is a function of the increase in temperature above the upper limit, where the main parameters are the duration of discomfort and its severity. Nonetheless, it has been shown that current overheating criteria have serious limitations as they are all educated guesses of what would be regarded as unacceptable.

Numerous studies, especially in the UK, have looked at overheating. While there is a general agreement on the most influential parameters, the role of building fabric promoting or hindering overheating is not as clear. It has been shown that there is, apparently, contradictory evidence on its performance. Regardless of the very different assumptions, locations, parameters, they all have used very different overheating criteria, most of which are now superseded. Only Mavrogianni et al. have done a statistical analysis of the temperatures developed in the dwellings, making their findings independent of them.

Besides the considerable amount of research, studies covering from low to high insulation levels with a full set of concurrent variables have not been located in the literature. Together with the lack of knowledge about acceptable overheating levels, it is still an open question how changes in the building fabric alter this risk. Hence, this paper will aim to characterize the relationship between overheating and building fabric, considering how reductions of the heating demand relate to them. Finally, it would be of interest exploring how sensitive findings are to different criteria to appraise the robustness of previous research in this field, as there is not yet a proper definition of overheating.

CHAPTER 3

Research methodology

The literature reviewed has shown how there is not still a robust criteria that can evaluate the overall performance, despite knowing the drivers of overheating. In addition, the reliance of most research in them and the differences in scope and methods have not been translated yet into a consistent characterization of how changes in insulation might affect the risk. Therefore, this chapter sets the hypothesis that will be tested to address the aim of the project together with the objectives and research methods required to prove or disprove them.

3.1 Hypotheses

To have a holistic perspective of what happens to overheating when increasing insulation the following hypotheses are proposed:

Hypothesis 1: 'Dwellings built to meet targets of low heating energy demand are less robust against overheating risk'. This will characterize the performance according to current knowledge of the drivers of overheating.

Hypothesis 2: 'Different overheating criteria do not show consistent risk trends between them'. This will detect whether conclusions about the performance of insulation depends on the criteria applied to test robustness of current methods and to try to explain why different studies have detected different behaviours.

Hypothesis 3: 'The ratio between relative increases in cooling and reductions of heating energy demand is less than one'. This comes back to the origin of the problem and will capture how changes in one demand affect the other.

3.2 Objectives

Table 3.1 shows the objectives through which hypothesis will be addressed.

Table 3.1: Objectives and research methods

Objective	Description	Research Method
1 Review of the literature regarding overheating and thermal comfort.	Critical appraisal of thermal comfort theory regarding overheating, current metrics, their differences and applicability range.	Desk-based: literature review of overheating in thermal comfort, standards and criteria.
2 Review of the literature regarding overheating in dwellings and its relationship with insulation.	Critically map and evaluate scope, gaps and discrepancies between overheating and insulation studies.	Desk-based: literature review of studies that relate overheating and insulation.
3 Develop a modelling method suitable for appraising the potential relationship fabric standards-overheating.	Produce and validate dynamic simulation modelling techniques to appraise changes in overheating risk. Perform parametric analysis.	Computer modelling and coding: use suitable software to simulate thermal performance and propagate parameter variations.
4 Evaluate the potential relationships fabric standards-overheating.	Explain the relationship between changes in insulation and properties of overheating risk.	Desk-based and coding: calculation of overheating properties and their summary into relevant formats.
5 Evaluate the results of applying different overheating criteria to overheating trends.	Contrast results obtained by applying current overheating criteria. Compare them with results obtained previously.	Desk-based and coding: calculation of overheating risks according to criteria and their summary into relevant formats.
6 Appraise changes in the relationship heating-cooling demand.	Summarize changes in energy demand balance when modifying the insulation levels.	Desk-based and coding: calculation of heating-cooling ratio and summary into relevant format.

3.3 Desk-based study

The literature reviewed in the previous chapter, together with building regulations and applicable standards, will inform the cases, parameters and ranges that should be studied to assess overheating, as well as their limits. Thermal comfort theory and relevant criteria will help deciding the indicators most suited to appraise the performance of models in each category. Based on the output of the analysis and through this method, it will be critically appraised how changes in building fabric translate into changes in overheating risk, if any.

3.4 Computer modelling

To perform parametric studies and predict likely internal temperatures, building simulation software will be used. According to the nature of these parameters and scope of the project, the dynamic simulation engine EnergyPlus (E+) is picked to account for the drivers of energy exchange and to allow easier propagation of relevant changes in the model as explained in section 4.2 (fig. 3.1). As overheating is especially sensitive to how internal temperatures evolve, the model will be first validated through a case study for which real performance data is recorded (fig. 3.2). The output of this process will set the core data upon which previous research method will build the analysis.

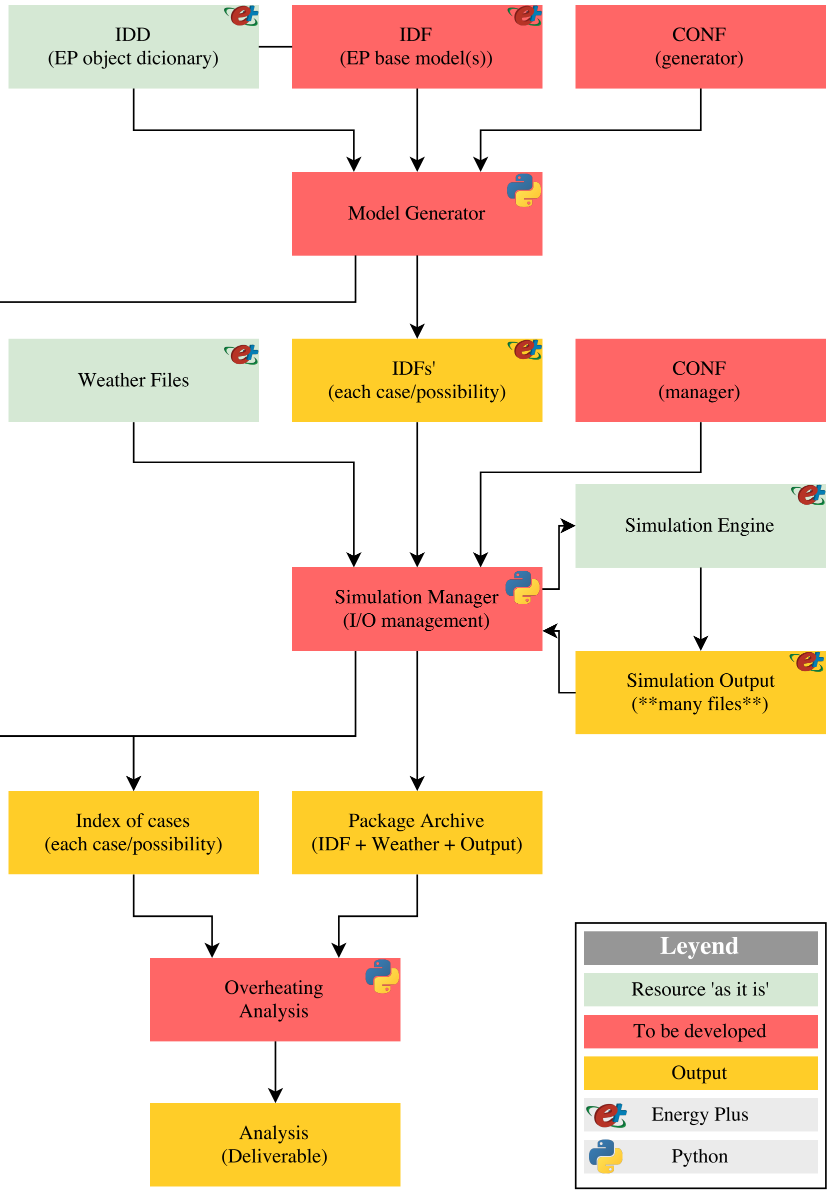


Figure 3.1: Parametric simulation

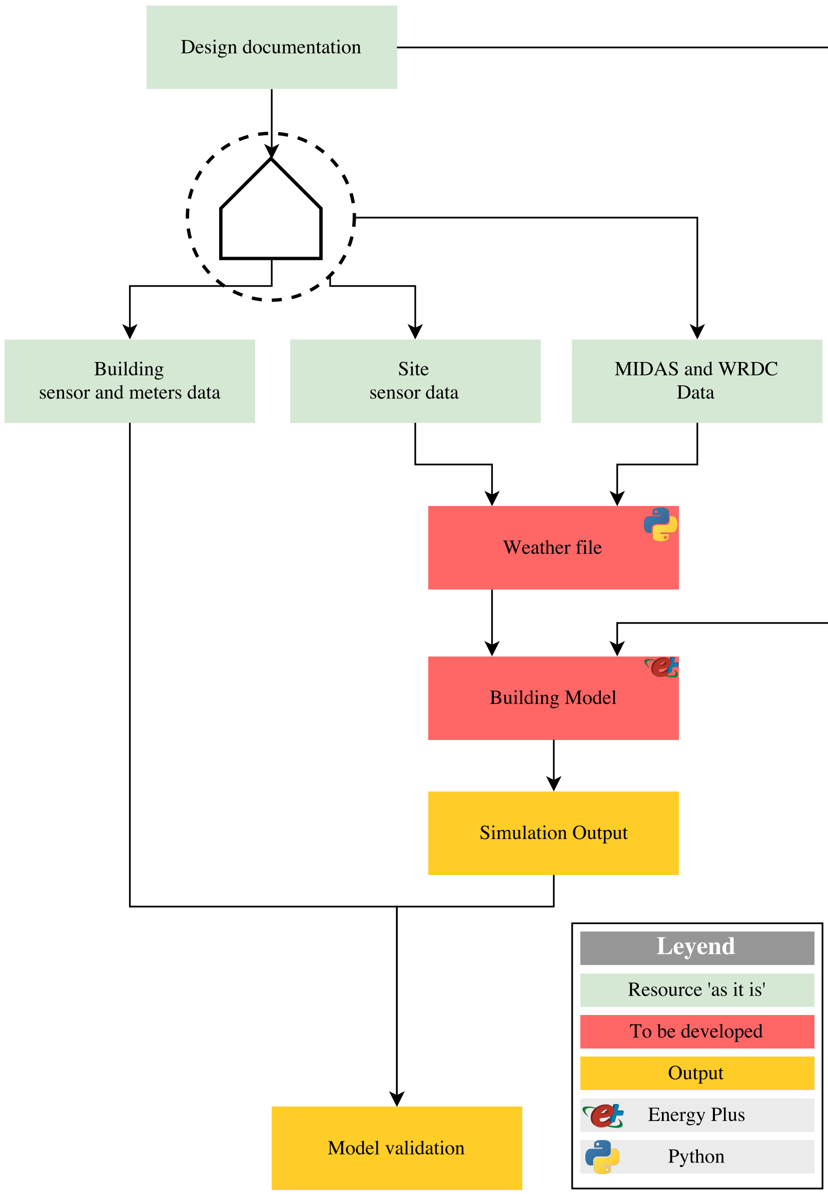


Figure 3.2: Validation of the simulation

3.5 Coding

To assist the process, several tools will be developed in Python. At the simulation step, they will be mainly focused in two areas, propagation of cases and input-output management, for which the project will make use of the libraries numpy, pandas, pytables and eppy. Another set of tools will process the large amount of data that results from parametric simulations. Thus, they will be aimed at the calculation overheating indicators and their analysis. These tasks will be carried through numpy, pandas, statsmodel, scikit-learn and seaborn. The results of this method will constitute the evidence through which address the objectives and answer the hypotheses of this project.

3.6 Boundaries and limits

The project will look at the domestic sector because not only does it represent the one at greater risk but also because it is the largest where specific typologies can be appraised. A highly insulated mid-terrace for which real measured data is available will be picked. It represents one of the types at higher risk and will allow for the validation of modelling methods (fig. 3.3). The constructions covered will start in the 90's and finish with a better-than-average PH to capture the meaningful spectre of insulation levels. As an initial assessment, three locations in the UK are chosen for the study: London, Manchester and Edinburgh. This way, regulations, standard of constructions, dwelling types and lifestyles will remain relevant across variations while appraising different sub-climates to capture the changes previous research has identified.

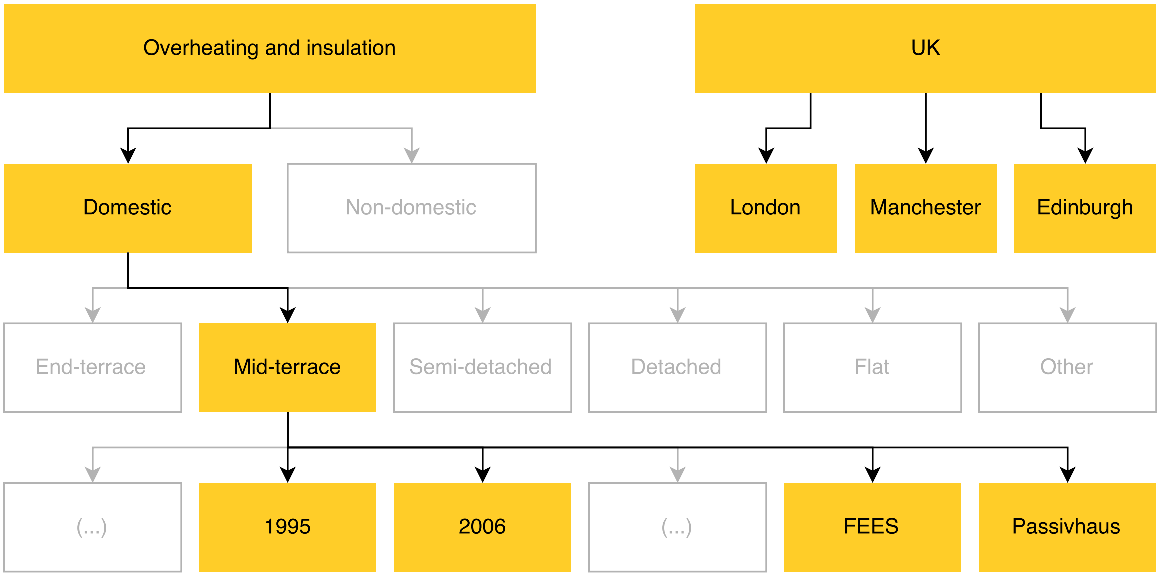


Figure 3.3: Boundaries and limits

CHAPTER 4

Simulation

This chapter specifies how research methods were used to address the hypothesis and objectives established in the previous one. Because of the interdependencies between them, they are presented altogether according to the logic of their implementation around the models. To begin with, the need of dynamic building simulations is reviewed to appraise its suitability for the project and to clarify its limitations, followed by the general characteristics of the one used in this paper. Then, the precise techniques to develop them and the chosen overheating criteria are specified in line with their appropriateness, followed by the description of the supplementary ones that were required. Lastly, a section is devoted to the validation process of these methods and the discussion of their results.

4.1 Monitored vs simulated buildings

The study of overheating and its relationship with the building fabric is complex because it joins thermal comfort with the physics behind a large number of variables. On the one hand, a limitation of overheating criteria in dwellings is that they are purely based on models developed from offices, as surveying comfort in dwellings has been traditionally challenging and it is still subject to further research (see section 2.1). On the other hand, the need to cover several parameters and their variations requires pairwise models, very unlikely to find in normal situations. Hence, these studies have relied on building simulations (see section 2.2). In this regard, the possibilities of model variables and ranges outweigh measured data. However, for this topic, simulations are aimed at predicting *temperatures*, not energy demand, task that requires a careful approach (Nicol et al. 2012). Because of this and the necessity of knowing occupants' perception, thermal comfort research focuses on field studies, advising building simulation when predictions are unavoidable (de Dear et al. 2013). As a result, none of these methods, by definition, answers every demand.

To mitigate the disadvantages of building simulation in the prediction of temperatures, it is then essential to validate the model to ensure that they are sensible, or at least to inform their confidence range. Thence, a real dwelling with available sensor and meter data has been chosen as the case study of this paper. Prior to the lunch of the parametric study, modelling techniques and assumptions will be appraised in this regard[1].

[1] In addition, it would have been desirable to appraise real overheating in this house. This belongs to current research by Rachel Mitchell, who kindly shared the information for this study.

4.2 Dynamic simulation

Dynamic building simulation was deemed the most suited type of model to address the objectives and test the hypothesis, mainly because it can capture the effects associated with different thermal mass, aspect for which the project is particularly sensible (section 4.3). Specifically, the study is done through E+ (LBNL 2015, Version 8.3.0), a robust tool extensively validated and used in research, which has these following advantages for the project:

Transparency: Every feature is fully documented, with a comprehensive explanation of the models (e.g. equations, limitations, intended use, interdependencies…) and detailed output and debugging information is available. The EnergyPlus Input Files (IDFs) can be viewed with a text editor, having complete control of what is being modelled. Furthermore, it is expanded according to the EnergyPlus Data Dictionary File (IDD), which contains the expected structure for each object, available to inspection as well.

Versatility: Models are based on objects. Thus, different aspects of the simulation (e.g. infiltration) can be isolated to a subset that communicates with the rest. Additionally, certain groups of objects implement different theoretical models, allowing the use of the most suited ones for the scope of the study (see sections 4.3.7 and 4.3.8).

Text based: Because input are just text files, they can be freely manipulated as long as the structure of objects follow IDD's directives. Since the study depends on parametric modelling to map different fabric standards, this allows for its split definition and the development of the custom tool that exclusively assembles relevant combinations (see section 4.3.11). Likewise, the output can be handled with scripts to manage multiple simulations and perform their analysis.

4.3 Modelling methods

This section describes how the model has been implemented according to the research requirements and the capabilities of the simulation engine. Firstly, the general description of the dwelling and common features to every case are described. Secondly, a number of subsections discuss each of the parameters to be explored. Lastly, a recap of the issues to take into account in the final assembly of variations is presented.

4.3.1 Base model

The case study is a mid-terrace that belongs to an urban development built on the late 2000 to meet the CSH Level 4, 'following the principles of Passivhaus' (fig. 4.1). Due to the conditions under which data was made available, only information that cannot be used to identify the actual occupants of the house will be discussed (see appendix A). The election of a terrace is based on that is the most common dwelling type prone to overheating, being ranked second to flats in overall risk (Palmer and Cooper 2013; ZCH 2015c). In this regard, studies agree on that the key difference between them lies in the options for natural ventilation, aspect considered as a variable (section 4.3.8). Among terraces, research has shown that end and mid-terraces are very alike, with the latter being at higher risk because they can only ventilate through two façades (Porritt et al. 2012; Gupta and Gregg 2013; Duckworth 2013). The election of a house built to these standards is due to the implied idea found in the literature that temperature changes in free running buildings are more sensible to increased levels of insulation (section 2.2). Moreover, they tend to have tighter controls, easing the validation as the documentation is more comprehensive than usual (section 4.6.1).

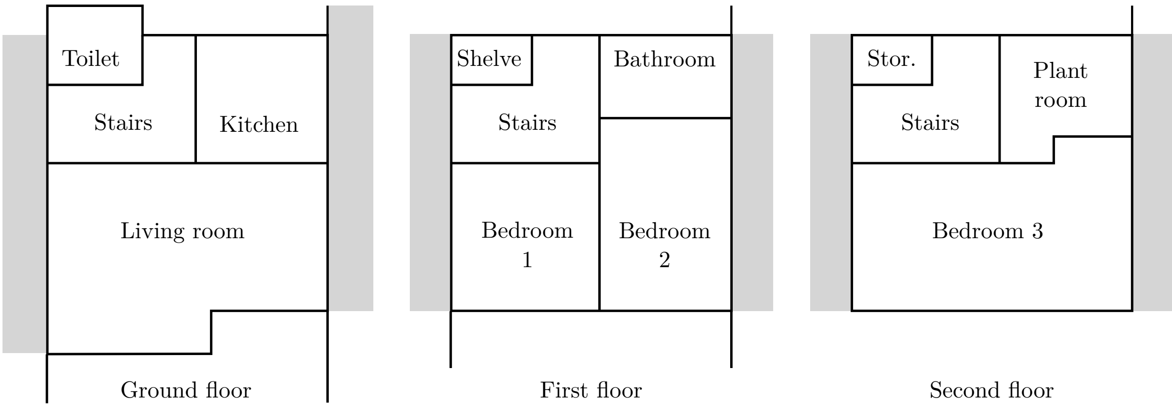


Figure 4.1: Geometry of the mid-terrace

The house has eleven rooms split in three storeys, with an average of $40\,\mathrm{m}^2$ per floor. The layout is conventional, with the third bedroom thought as a double room/home office. Due to the scope of this paper, each room is modelled as a separate zone to have individual temperature readings. Furthermore, the solar distribution model used ('FullExterior') assigns solar gains to the floor (LBNL 2015)[2]. Hence, this method achieves better resolution for the location of gains. Following the PH calculation methods, the house has been modelled to the external side of the thermal envelope. From there, areas and volumes are assigned according to the fabric (sections 4.3.2 and 4.3.3). The boundary conditions are:

Ground floor: outdoors, exposed to wind. According to construction details, the house features a suspended floor with a vented cavity.

Façades: outdoors, exposed to wind and sun.

Party walls: adiabatic. This speeds up calculations and simplifies the analysis, being congruent with the scope of the project (higher insulation). Otherwise, it would have been necessary to define adjacent houses with different gains and schedules to have energy transferences here. Still, thermal mass of these walls is still taken into account.

Internal walls/floors: Energy transferences are modelled to capture the effect of increased gains in certain rooms (i.e. kitchen and plant room).

The last shared feature is heating, modelled as `ZoneHVAC:IdealLoadsAirSystem`. This object is recommended to study the energy demand without modelling building services in detail, which considers a 100% efficiency. To cover the objectives regarding the winter–summer balance and to satisfy thermal comfort models, this system should have been modelled to control *operative temperatures*. However, common sensors control *air temperatures*, which yield lower demands than with the previous temperatures. In order to have a one comparable to those published, the latter control was modelled.

[2] All references made to E+ (their objects, models, properties and equations) are based on the official documentation found in LBNL 2015. The reader is referred to them as the source, being explicitly cited when omission might lead to confusion.

4.3.2 Fabric standards

To satisfy research goals, four fabric standards were considered ranging wall U-values of 0.45–0.10 $\mathrm{W\,m^{-2}\,K^{-1}}$ (table 4.1; by '1995' and '2006' it is meant a dwelling built to satisfy 1995 and 2006 UK regulations, respectively). 1995 was chosen because of two reasons. Firstly, the studies that link greater insulation with higher overheating agree on that post-2000 dwellings suffer a noticeable increment in the risk, being somewhat the same for older constructions (Dengel and Swainson 2012). Secondly, they provide a range wide enough to overcome the limitations identified in the literature review, but still within sensible limits and overlapping with retrofit ranges. 2006 serves as the baseline for post-2000 houses and FEES represent current good-practice standard. Finally, a 'better-than-average' PH insulation is established to cover high insulation levels. Beyond insulation, each of these standards also entails further conditions such as airtightness or ventilation but since these are treated as variables, they will be discussed later on.

Table 4.1: Definition of the building fabric: U-values and glazing properties

	1995	2006	FEES	PH	Unit
U-value$_{Wall}$	0.45	0.35	0.18	0.10	$\mathrm{W\,m^{-2}\,K^{-1}}$
U-value$_{Roof}$	0.25	0.25	0.13	0.10	$\mathrm{W\,m^{-2}\,K^{-1}}$
U-value$_{Ground}$	0.45	0.25	0.18	0.10	$\mathrm{W\,m^{-2}\,K^{-1}}$
U-value$_{Door}$	3.30	2.20	1.40	0.85	$\mathrm{W\,m^{-2}\,K^{-1}}$
U-value$_{Window,limit}$	3.30	2.20	1.40	0.85	$\mathrm{W\,m^{-2}\,K^{-1}}$
U-value$_{Window,real}$ [a]	3.30	2.20	1.30	0.76	$\mathrm{W\,m^{-2}\,K^{-1}}$
g-value	0.74	0.70	0.60	0.59	—
Light transmission	0.80	0.76	0.76	0.69	—
Window layers	4+6+4	4+8+4	4+16+4	5+12+4+12+5	—

[a] ISO-10292/EN-673

The opaque envelope has been designed to meet exactly quoted limits. In reality, they would be adapted to reasonable insulation thicknesses, but since different thermal mass was also taken into account, this could have added unnecessary complexity to the analysis (section 4.3.3). On the contrary, glazing has been kept as real as possible because their thermal and optical properties start to conflict as standards impose higher insulation. Thus, windows have been modelled with data from manufacturers, specifying full spectral data for units with coatings (FEES–PH, table 4.1).

4.3.3 Thermal mass

The opaque envelope is determined by the U-value and thermal mass. This parameter has a special importance to address the objectives as it was often mentioned in the literature that the performance of insulation was a function of it. The SAP overheating check shows decreases up to 4 K when moving from low to high thermal mass, a difference equal to TM-52 third criterion (fig. 4.2). The TMP was used to summarize the performance as it is the standard for SAP, being established as 28 for low, 281 for medium and 520 $\mathrm{kJ\,m^{-2}\,K^{-1}}$ for heavyweight, seeking to capture equivalent increments from the midpoint. These values are obtained by multiplying the areas of the constructions by the heat capacity, expressed as K_m, since it takes into account the depth that is thermally active (table 4.2). These calculations were carried through the Dynamic Thermal Property Calculator developed by Arup, which implements ISO-13786 and ISO-13790 methods (The Concrete Centre 2010). This way, norm-compliant characterization of its behaviour (e.g. thermal admittance, time lead, decrement factor) is available prior to the simulation, helping its definition. The timestep of the simulation was adapted to six per hour (each 10 min) as a balance between accuracy and runtime.

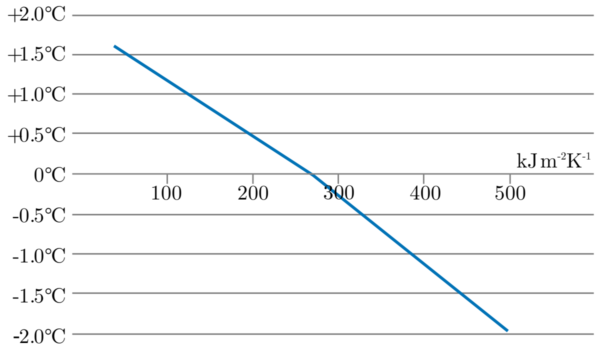


Figure 4.2: "SAP overheating check — reduction in internal temperature for light, medium and heavyweight homes with night ventilation" (The Concrete Centre 2015, Figure 8) (adapted from original).

Table 4.2: Thermal mass summary*

		Lightweight		Mediumweight		Heavyweight	
	A [m^2]	K_m	$K_m \cdot A$	K_m	$K_m \cdot A$	K_m	$K_m \cdot A$
External Wall	173	7	1211	114	19722	168	29064
Roof	60	7	420	33	1980	190	11400
Flat Roof	6	7	41	33	193	190	1112
Internal Wall	98	7	686	7	686	7	686
Internal Floor	76	16	1218	93	7077	191	14535
Ground Floor	52	25	1309	123	6440	191	10001
TMP	[kJ m^{-2} K^{-1}]	—	38	—	281	—	520

* K_m [kJ m^{-2} K^{-1}] calculated according to ISO-13790.
TMP referred to the total *floor area* of the house.

The layer structure for lightweight constructions relies, essentially, in internal insulation, whereas for medium and heavyweight scenarios it is external (tables B.1 to B.6). Here internal layers were adapted to reach the TMP goal. Because of K_m-based approach, constructions could be serialized for each standard by changing the insulation thickness (conductivity of 0.04 W m^{-1} K^{-1}), where any form of air cavity insulation was avoided as modelling its real performance involves further simplifications. Internal partitions were taken as a wildcard to fine-tune the TMP, reason why they were finally lightweight. This way, the elements affecting main energy transferences and storage in E+ are physically accurate. The only worth-mentioning simplifications are that the thermal mass was considered fully exposed and that older houses feature lower-than-usual thicknesses because of the serialization based on same insulation and thermally meaningful layers. The reasons for these were to keep them as controlled variables.

Table 4.3: Extract of volumes and areas* (table B.7)

Case	TM	Living room		Bedroom 1		Bedroom 2		Bedroom 3		Total	
		V [m^3]	A [m^2]	V [m^3]	A [m^2]	V [m^3]	A [m^2]	V [m^3]	A [m^2]	V [m^3]	A [m^2]
	L	59	25	27	11	30	13	49	22	279	122
FEES	M	57	24	26	11	29	12	42	22	260	118
	H	56	24	25	11	29	12	41	21	255	114

Key: *L*ow, *M*edium, *H*igh. * Volumes and areas of main living spaces, with the total for the whole house.

Areas and volumes for each of the twelve combinations of standard and thermal mass were worked out accordingly (table 4.3). To reflect these, the object `Zone` allows for direct input of areas and volumes —instead of being automatically calculated—, so the energy exchange is invested in the real enclosed air. A further consequence derives from the solar heat gain model, which takes into account frames, dividers and reveals of windows (table 4.4). To maintain same conditions among constructions, these were specified with the same recess (5 cm) from the outer layer.

Table 4.4: Extract of frame and dividers geometrical definition according to age and thermal mass (table B.8)

Case	TM	Wall (bare) [cm]	Wall (total) [cm]	Glass [mm]	Recess [cm]	Reveal [cm]	Frame [cm]
	L	8.0	24.3			16.9	
FEES	M	9.0	30.0	24	5	22.6	10
	H	13.5	34.3			26.9	

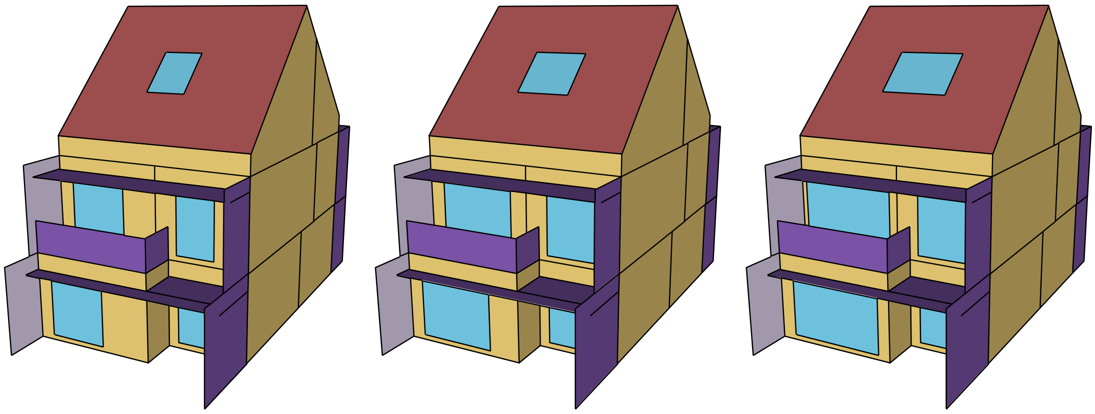
Key: *L*ow, *M*edium, *H*igh.

4.3.4 Glazing

Openings have a major influence on the energy balance of a building, being necessary a careful dimensioning of all its aspects (dimensions, thermal and optical properties and shading strategies). The documentation of the project showed, in independent reports, that the house had an adequate winter–summer balance. Interestingly, original plans featured significantly more glazing than that corroborated as built. The corrected value is a glazing-to-floor ratio[3] of $\approx 21\%$ —remarkably close to traditional good-practice recommendations— taken as the baseline. From this, cases explore variations of $\pm 5\%$ for the high and low glazing variants (fig. 4.3).

Frame and dividers configurations have been considered as in the project, adapting frame dimensions into two groups, one for 1995–2006 and other for FEES–PH, so they are coherent

[3]The preferred metric has been glazing-to-floor ratio because of the characteristics of a mid-terrace.



(a) **Low:** 16% (b) **Medium:** 21% (original) (c) **High:** 26%

Figure 4.3: Glazing definition (wall-to-floor glazing ratios)

with their constructions. The geometry of the model accounted for the E+ convention of defining openings based on the glazed area. From this, frames are subtracted from the remaining opaque envelope, whereas dividers are taken from the glazing area. The thickness of the dividers was maintained between constructions to keep solar gains constant among them. As a simplification, the conductance of frame and dividers was taken as that of the glazing ratio so different opening sizes do not have to be characterized individually, reason why thermal properties of glazing was chosen close to their limits. Finally, changes in dimensions where done in such way that they kept their shading conditions (section 4.3.5).

4.3.5 Shading

The original building has an optimal orientation, with living spaces 10° off south. The house features numerous shading devices in the main façade, which maintain most of the glazing shadowed during peak hours in the summer, with the exception of the biggest window in the living room. In addition, this type of building can be regarded to have specific urban shading conditions based on the repetition of the model (offset taken as 15 m). The winter–summer balance previously mentioned was cross-checked with ClimateConsultant© (UCLA Energy Design Tools Group 2015), showing that the average angle at about 50° performs adequately for the real weather file (section 4.6.1).

These shading conditions were taken as an acceptable upper limit because they rely on fixed elements that provide, apparently, adequate performance *by default*. While it is true that adapting shading conditions during the year has greater potential, they entail, in practical terms, occupant operation (even more so in dwellings). The modelling of their behaviour is among the challenges of defining a simulation because it greatly influences its performance through shading, gains and ventilation strategies. Mavrogianni et al. (2014), in the paper where they address this in retrofits, concluded that this kind of data is not currently available and that different estimations result in very different risks. Logically, options are endless (e.g.: trigger shading by temperature and/or solar radiation, allow for it when occupied, set default states before leaving the house and so on).

Hence, original shading is maintained, updating northern devices to meet same angles as the southern ones so when different orientations are explored they remain appropriate. The only simplification was done to bedroom 3, where a shading device with optimal operation based on temperature was included as means to approximate good shading conditions due to its location (table 4.5). Overall, this default state constitutes the best-case scenario, defining the worst-case as no shading but that of the urban landscape, considering that other ones would fall between or close to these values.

Table 4.5: Definition of shading device in bedroom 3 through E+ `WindowMaterial:Shade`

Property	Value	Unit
Solar Transmittance	0.1	—
Solar Reflectance	0.8	—
Visible Transmittance	0.1	—
Visible Reflectance	0.2	—
Infrared Hemispherical Emissivity	0.9	—
Infrared Transmittance	0	—
Thickness	0.5	cm
Conductivity	0.1	$\mathrm{W\,m^{-1}\,K^{-1}}$
Shade to Glass Distance	5	cm

4.3.6 Internal gains

Internal gains feature a similar complexity to that of shading and ventilation behaviour. Similarly to shading, a sound aim was to find the likely boundaries of their influence through high and low estimations based on educated guesses informed by current practices. As usual, these have been grouped in occupancy, lighting and equipment gains.

The occupancy is established according to the size of the house and the characteristics of the bedrooms. Because the third one has twice the typical area, an additional occupant was considered there, resulting in a total of five for the high scenario. The low would be three occupants, a number in the lines of PH methodology ($35\,\mathrm{m^2/\,p}$). Based on this, two occupancies are proposed: a working family of five members where parents and children are way during working/school hours, from 9:00 to 17:00, and three pensioners/unemployed home all-day-long ('high' and 'low' scenario, respectively). The only purpose this analogy is to inform subsequent estimations but in terms of overheating, they explore two meaningful cases: constant low occupancy or high after peak temperatures, in the same fashion of reviewed studies. These were translated in hourly activities for each of the relevant spaces: living room, bedrooms and kitchen. The different activities during daytime give about $120\,\mathrm{W/\,p}$ on average (table 4.6) which, in addition to the variation in occupancy, result in significant changes. Whether a person is occupying a particular space is considered irrelevant but what this gain can represent is not.

$$M = S + L \tag{4.1}$$

$$\begin{aligned} S = {} & 6.461927 + 0.946892M + 0.0000255737M^2 + 7.139322T_{air} - 0.0627909T_{air}M \\ & + 0.0000589172T_{air}M^2 - 0.198550T_{air}^2 + 0.000940018T_{air}^2M \\ & - 0.00000149532T_{air}^2M^2 \end{aligned} \tag{4.2}$$

Table 4.6: Occupancy gains* (Data source: CIBSE (2015))

Room	Activity	
	[met/p]	[W/p]
Living room	1.1	115
Kitchen	1.5	157
Toilet / Bathroom	1.2	125
Bedrooms (day)	0.9	94
Bedrooms (night)	0.7	73

* E+ `People` is defined by metabolic rate per person. Sensible and latent fractions are calculated according to eqs. (4.1) and (4.2).

The definition of lighting and equipment gains are also opened for discussion because they are linked to occupancy, behaviour and often related to the age of construction. Richardson et al. (2010) developed a tool that generates high-resolution electricity demand based on field studies, but a model coherent with this would need to implement sub-hourly data, different from one day to the other, to benefit from this approach, making the analysis more complex (different runs should yield different temperatures). As a reference, sample runs of the tool gave, for a house of these characteristics, an average of $\approx 3.98\,\mathrm{W\,m^{-2}}$. On the other hand, PH defaults to $2.1\,\mathrm{W\,m^{-2}}$ to appraise overheating, known to be lower-than-average because it seeks the optimization of internal gains as well. For their study, McLeod et al. (2013) adapted PH levels to reflect UK consumption profiles, arriving at values within these limits ($3.69\,\mathrm{W\,m^{-2}}$).

Table 4.7: Definition of internal gains based on PHPP: profile 1 (5 persons, average $3.83\,\mathrm{W\,m^{-2}}$)*

Application	Base	Unit	Frequency		Quantity		kWh/ a	Wh/d	W/ h
Dishwasher	1.0	kWh/ use	73.0	$(p \cdot a)^{-1}$	5	p	358	979.45	40.81
Washing m.	1.2	kWh/ use	52.0	$(p \cdot a)^{-1}$	5	p	312	854.79	35.62
Dryer	3.5	kWh/ use	52.0	$(p \cdot a)^{-1}$	5	p	910	2493.15	103.88
Fridge	1.0	kWh/d	365.0	$d \cdot a^{-1}$	1	—	365	1000.00	41.67
Cooking	0.3	kWh/ use	730.0	$(p \cdot a)^{-1}$	5	p	913	2500.00	104.17
Lighting	60.0	W	2.9	$\mathrm{kh}(p \cdot a)^{-1}$	5	p	870	2383.56	99.32
Consumer	80.0	W	0.6	$\mathrm{kh}(p \cdot a)^{-1}$	5	p	220	602.74	25.11
Other	50.0	kWh	1.0	$(p \cdot a)^{-1}$	5	p	250	684.93	28.54
Total	—		—		—		4197	11498.63	479.11

* Figure based on average area of all cases.

For this study, they have been based on PHPP methodology as well, but customizing the values according to occupancy and activities. The averages result in $3.83\,\mathrm{W\,m^{-2}}$ for the high occupancy and $3.03\,\mathrm{W\,m^{-2}}$ for the low one (tables 4.7, 4.8 and B.12). Appliances were specifically modelled in the kitchen and in the plant room to consider the potential influence they can have in adjacent spaces (due to its size, the plant room was taken to serve as laundry room as well). The rest was based on educated guesses (e.g. TV in the living room, laptops in bedrooms, stand-by loads…). Beside these, bedroom 3 was taken as an office during working hours for the low occupancy scenario, reason for which the budget of this case was risen to office levels.

Table 4.8: Summary of lighting gains*

Hour	Lighting*	Schedule
Profile 1: 5p	4.92 $\mathrm{W\,m^{-2}}$	07:00–08:00 and 19:00–23:00
Profile 2: 3p	4.02 $\mathrm{W\,m^{-2}}$	07:00–08:00 and 19:00–23:00

* Defined as per PHPP-based budget. The area for this ratio was taken as that of occupied spaces.

4.3.7 Infiltration

Infiltrations are closely related to fabric standards, each of which results in different permeabilities. These have been estimated according to research, regulations or their specific targets (table 4.10). Often, buildings are studied taking into account an average constant air change. For the scope of the project, this was deemed inappropriate because it is a function of the weather conditions: an average could lower overheating risk or the heating demand because of the combination of wind and stack effect. E+ allows for three different models, based on those by Coblenz and Achenbach (1963), Sherman and Grimsrud (1980) and Walker and Wilson (1998). Of these, the latter one was implemented (`ZoneInfiltration:FlowCoefficient`) because it is especially advised for a dwelling of these characteristics (ASHRAE 2013). Furthermore, it also takes into account its exposure and geometry (eq. (4.3) and table 4.9).

$$Infiltration = (F_{Schedule}) \sqrt{(c\,C_s \Delta T^n)^2 + \left(c\,C_w (s \cdot v_w)^{2n}\right)^2} \tag{4.3}$$

Table 4.9: Infiltration: E+ input data for `ZoneInfiltration:FlowCoefficient`

Parameter	Symbol	Units	Value
Schedule[a]	$F_{Schedule}$	—	1
Flow coefficient[b]	c	$\mathrm{m^3\,s^{-1}\,Pa^{-n}}$	table 4.10
Stack coefficient[c]	C_s	$\mathrm{(Pa/K)^n}$	0.078
Pressure exponent[c]	n	—	0.67
Wind-induced infiltration coefficient[c]	C_w	$\mathrm{(Pa\,s^2/m^2)^n}$	0.17
Shelter factor[c]	s	—	0.5

[a] Always on. [b] The flow coefficient in table 4.10 was adapted per zone according to its external envelope area. [c] Values from ASHRAE (2013) for this case study.

The flow coefficient was estimated based on the airtightness, taking 0.67 for the flow exponent as an approximation (ASHRAE 2013). To take fully advantage of the weather-driven

Table 4.10: Infiltration: definition of cases[*]

Case		q_{50} [$m^3\,h^{-1}\,m^{-2}$]	$\dot{V}_{50}$ [$m^3\,h^{-1}$]	n_{50} [$ach@50Pa$]	n [ach]	$\dot{V}_{50}$ [$m^3\,s^{-1}$]	c^a [$m^3\,s^{-1}\,Pa^{-n}$]
	H	30.00	9540	32.34	2.264	2.6500	0.192724
1995[a]	M	20.00	6360	21.56	1.509	1.7667	0.128483
	L	10.00	3180	10.78	0.755	0.8833	0.064241
	H	10.00	3180	10.97	0.768	0.8833	0.064241
2006[b]	M	7.00	2226	7.68	0.537	0.6183	0.044969
	L	5.00	1590	5.48	0.384	0.4417	0.032121
	H	4.00	1272	4.82	0.337	0.3533	0.025697
FEES[c]	M	3.00	954	3.61	0.253	0.2650	0.019272
	L	2.00	636	2.41	0.169	0.1767	0.012848
	H	0.50	139	0.60	0.042	0.0387	0.002812
PH[d]	M	0.37	104	0.45	0.032	0.0290	0.002109
	L	0.25	70	0.30	0.021	0.0193	0.001406

Key: *L*ow, *M*edium, *H*igh.
[*] Flow coefficient considering Δ50Pa and $n = 0.67$.
[a] Data for q_{50} and ranges from CIBSE (2000).
[b] Data for q_{50} and ranges from ODPM (2006b) and ODPM (2006a).
[c] Data for q_{50} from ZCH (2009), ranges from ODPM (2013b).
[d] Data for q_{50} derived from n_{50} (Cotterell and Dadeby 2012).

infiltration model, it was modelled individually for each room, prorating it according to the envelope area following airtightness criteria. To keep it as a controlled variable within same building fabric, internal envelope area was taken as constant regardless of the thermal mass (table B.9). To account for the dispersion in airtightness, a high and low scenario has been taken around expected mean values.

4.3.8 Ventilation

Ventilation is organised in three groups according to their purpose, namely CO_2-oriented, extract for wet rooms and purge ventilation. Again, specific systems are function of the age of construction, and, in this case, of the airtightness as well. On the one hand, a code-compliant system for 1995 dwellings was based on background ventilation using trickle vents. In 2006, this system was also advised for buildings of the considered q_{50} (ODPM 2006b). On the other hand, two changes take place beyond this: higher flow rates are specified (infiltration ones are low enough to be neglected in CO_2 calculations) and the house starts to benefit from MVHR. In PHs, higher flow rates are specified in the pursue of higher comfort, being mandatory the use of a MVHR unit to lower the energy demand. These successive increments of the flow rates further support the appropriateness of modelling wind-and-stack driven infiltration. PHs have CO_2-oriented ventilation of about 0.35ach whereas infiltration in 1995 has an average of 1.5ach. Still, they cannot be simply added because natural drivers could yield high CO_2 levels temporarily. Extract ventilation remained constant between building regulations, although in a PH they are lower. Building regulations establishes a purge ventilation sized to an opening equal to 1/20 of the floor area, a value that is expected to give 4*ach* in the UK (ODPM 2013b). To be congruent with the ACMs, this feature has also been considered for the PH.

Among all these systems, it can be noted a high reliance on natural ventilation: 1995–2006 background ventilation and purge for everyone. This is a sensitive issue as it can be concluded that robust methods to predict its performance are simply not available because of the endless considerations that drive these flows in reality (e.g. urban landscape, properties of openings and locations within the room, to name a few). On top of these, occupant behaviour should be added, of paramount importance in the case of purge ventilation and overheating risk. This information is also unavailable (Mavrogianni et al. 2014). Finally, current approaches for annual performance rely on modelling zones as a *node*, although a number of techniques have been implemented in E+ to account for different air distributions within the zone. Here, natural ventilation can be modelled through three groups of objects, which can be ranked in complexity according to the number of physical properties they implement. Between these, the `ZoneVentilation:WindAndStackOpenArea` was chosen because it requires what was deemed a *reasonable* amount of inputs for a house whose specific opening properties have not been measured, while it is still linked to the natural drivers (eqs. (4.4) to (4.8)) and keeps acceptable simulation runtime.

$$Ventilation = \sqrt{{Q_s}^2 + {Q_w}^2} \tag{4.4}$$

$$Q_w = C_{w,vent} A_{opening} F_{schedule} v_w \text{ where } C_{w,vent} = 0.55 - \frac{|\mathrm{EA} - v_{dir}|}{180} \cdot 0.25 \tag{4.5}$$

$$C_{w,vent} = 0.55 - \frac{|\mathrm{EA} - v_{dir}|}{180} \cdot 0.25 \tag{4.6}$$

$$Q_s = C_D A_{opening} F_{schedule} \sqrt{2g\Delta H_{NPL} \frac{|T_{zone} - T_{db}|}{T_{zone}}} \tag{4.7}$$

$$C_D = 0.40 + 0.0045\,|T_{zone} - T_{odb}| \tag{4.8}$$

As a result, the systems implemented in the model are:

CO_2-oriented ventilation: 1995–2006 dwellings have been modelled with the mentioned object for natural ventilation, sized accordingly to building regulations (table 4.11). Likewise, FEES has MV as derived from its air leakage (ODPM 2006b). Finally, PH has a MVHR unit with 75% efficiency, which is by-passed when needed.

Extract: For FEES and PH, the MV has been balanced per storey according to activities: when cooking the supply in the living room is increased accordingly (tables B.13 and B.14). For 1995–2006 cases, specific extraction fans were considered, neglecting air transferences between zones because they represent a small proportion when compared to infiltration, as seen before.

Purge: This constitutes the parameter of study. Three cases are modelled to explore the limits performance. In the first, no purge ventilation is allowed to have a baseline for the worst-case scenario. In the second, it is during daytime (07:00-23:00) as long as there

Table 4.11: Background ventilation for 1995 and 2006*

Room	Purge [m^2]	Background [mm^2]	Extract [$L\,s^{-1}$]
Living room	1.36	8000	—
Kitchen	0.49	4000	60
Toilet	0.20	4000	15
Stairs	1.16	8000	—
Bedroom 1	0.61	8000	—
Bedroom 2	0.70	8000	—
Bathroom	0.29	4000	15
Storage	—	—	—
Bedroom 3	1.21	8000	—
Plant room	—	4000	30
Shelve	—	—	—
Total	—	56 000	—

* Purge (rapid ventilation) remains the same under FEES and PH cases.

are occupants in the house. Likewise, the third allows it 24 h with the same occupancy restrictions.

Behaviour has been considered *opportunistic*, as per ACMs, being activated when the free-running comfort temperature is surpassed and the external temperature is lower than the internal. This has been implemented through an hourly temperature schedule defined consistently with the detailed calculations of the EN-15251[4] (fig. 4.4). Since most significant heat gains take place during the day, the proposed purge strategies would yield approximately the same overheating results. Night-time purge is more advantageous if it cools down the thermal mass of the house over the night beyond what is strictly necessary. Consequently, windows are opened until they meet the lower comfort threshold in this scenario to quantify the improvement (fig. 4.5).

Lastly, terraces allow for cross-ventilation. Only `AirflowNetwork` objects can account for naturally driven air exchange between zones in E+, provided detailed inputs whose values are unknown for both openings and behaviour. To overcome this, it has been assumed that if the building overheats, occupants would open windows and internal doors, allowing air exchange between zones. As a result, it was also assumed that under these circumstances, the temperature of the zones would *tend to the average* between them. Thus, `ZoneMixing` objects with a high flow rate were modelled.

4.3.9 Orientations

Four orientations were taken into account to approximate every possibility. The only relevant adaptation would have been the shading strategies, if the house was not as shaded as it is by

[4]The running mean was calculated through the general method as opposed to the simplified one due to the error it can yield (fig. B.5).

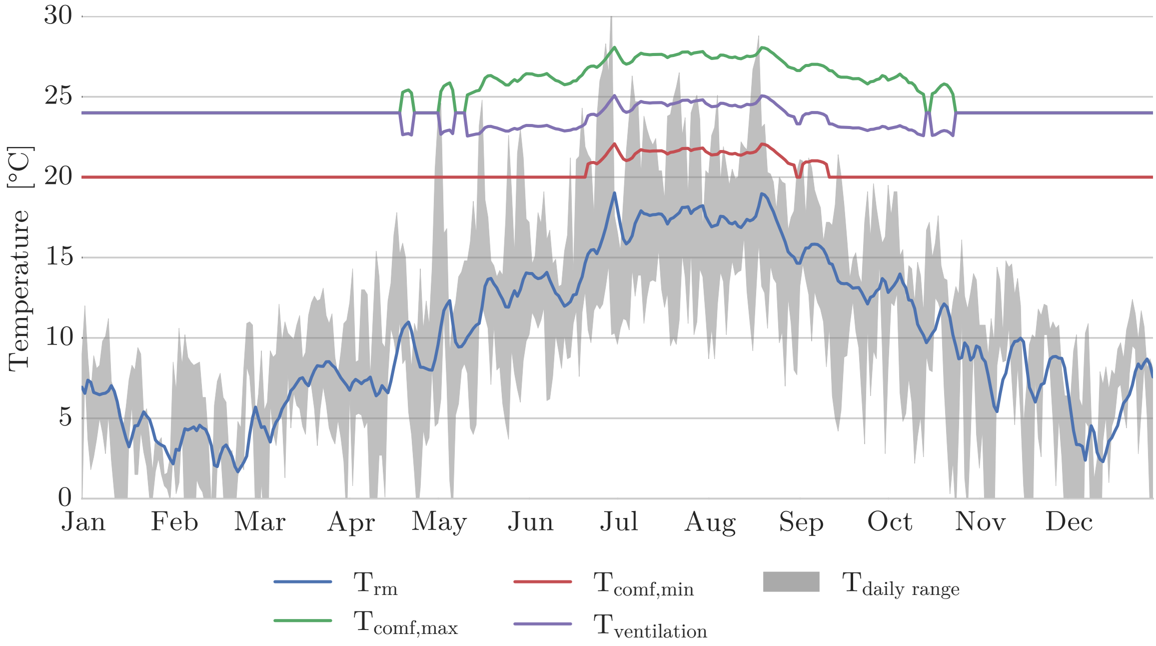


Figure 4.4: London purge ventilation temperature trigger: Day

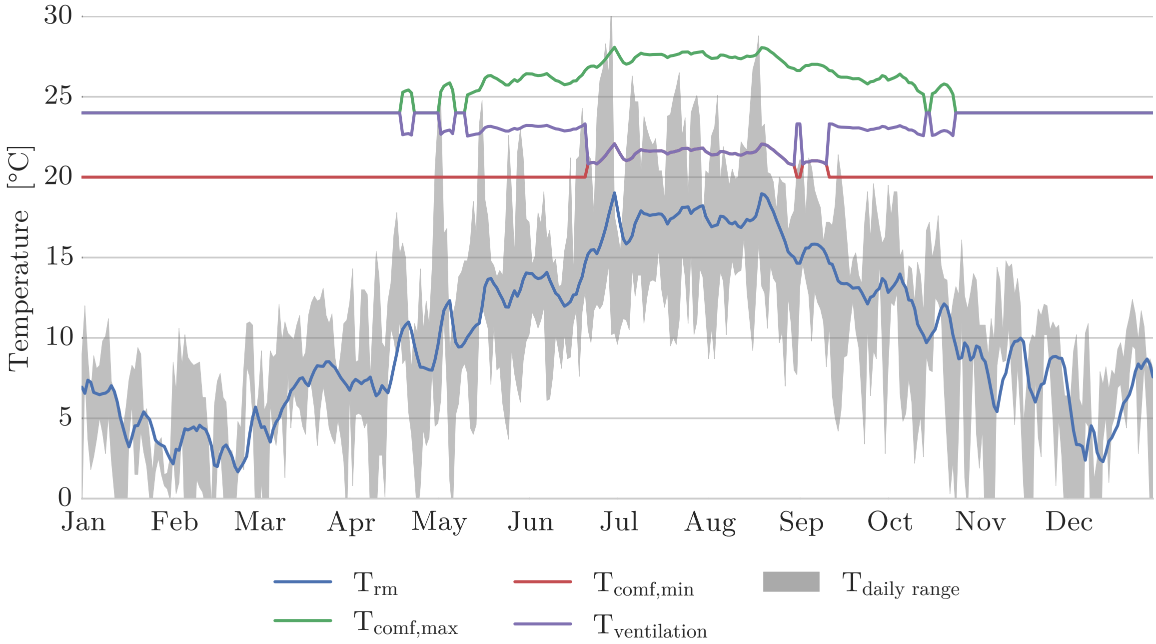


Figure 4.5: London purge ventilation temperature trigger: Night

default. Thus, the sizes of shading devices in the original north façade have been changed so it featured equivalent conditions to those of the southern one, as mentioned in section 4.3.5.

4.3.10 Locations

The locations considered were London, Manchester and Edinburgh to approach an overall overheating performance in the UK. The house remained the same between these to simplify the analysis (pairwise comparisons), assuming that changes in latitude do not change the geometry of the shading, as this would have needed specific studies of winter–summer performance. This was deemed acceptable, as northern locations would have greater heating demand but also greater solar gains. Due to the known problems with DSY files, TRY were used to carry out the simulations (Jentsch et al. 2014).

4.3.11 Parametric modelling

As it has been explained, each building standard entails a different implementation of certain parts of the model. This was specifically addressed so combinations remained consistent with real scenarios. Thus, the model was carefully split between several IDF according to each parameter. In this regard, the cases of thermal mass and ventilation were particularly demanding as they featured conditions based on other parameters. For instance, ventilation required auxiliary files to define the ventilation systems based on age of construction and occupancy, whereas two of purge strategies were a function of the occupancy alone. Altogether, these parameters generate 3456 model/ location (table 4.12).

Table 4.12: Summary of parameters: 3456 simulations/location

Cases	Standard	Thermal mass[a,b]	Glazing	Shading	Internal gains	Infiltration[a]	Purge[a]	Orientation
1	1995	L (38)	L (16%)	Urban	Family (5p)	L	No purge	N
2	2006	M (281)	M (21%)	Full	Pensioners (3p)	H	Purge day	E
3	FEES	H (520)	H (26%)	—	—	—	Purge night	S
4	PH	—	—	—	—	—	—	W
Total	4	3	3	2	2	2	3	4

Key: *L*ow, *M*edium, *H*igh.
[a] Parameter dynamically adapted according to context (concurrent variables).
[b] Thermal mass expressed as TMP ($\mathrm{kJ\,m^{-2}\,K^{-1}}$).

4.4 Overheating indicators

Given the state of the art and the research questions, the following groups of overheating indicators were considered:

Independent overheating characterization: Because current criteria are deemed to expire given the limitations they have, this set of indicators will help to understand what is happening beyond Pass/Fail tests. They assess the performance of what is known to be properties of comfort. Until further research arrives at a framework that allow the optimization of overheating strategies, it is considered more appropriate to summarize simulations with these annual values.

Duration: Count of occupied hours above upper EN-15251 Category II threshold.

Severity: Breakdown of temperatures (1) and occupied hours by $\Delta T_{cm,max}$=1 K bins when occupied and above upper EN-15251 Category II threshold (2).

Discomfort: PPD-weighted occupied hours above upper EN-15251 Category II threshold.

Specific overheating criteria: These are used to test the hypothesis that different criteria yield different trends. Due to their popularity, the TM-36, TM-52 and PH will be tested. Additionally, these criteria have been the reference point for most research projects. Therefore, it would be of value to add up to this body of knowledge in the ways they already used.

Energy demand balance: To appraise the balance winter–summer, a fictitious cooling set-point is established for those hours where the room overheats, being adaptations enough to satisfy comfort for the rest of the time. This approach has to be understood as an estimation because the energy balance of an actively cooled room is different to that of a free-running one. Thus, the indicator is CDD when occupied and above upper EN-15251 Category II threshold, with set-point to 25 °C (as per PPD-PMV model).

4.5 Auxiliary methods

The number of simulations resulting from the minimal parameter sweep and the conditional modelling based on standards made necessary the development of scripts, which eased not only their creation but also their management and analysis. Developed in Python, they can be grouped as:

Helpers: To ensure the feasibility of splitting the IDF and to help during the process, a number of functions were developed to analyse E+ objects and IDD. Figure 4.6 offers an example of the function developed to map dependencies from the properties of one object to others.

EPGenerator: Combinations had to be populated in two steps. Although the model was developed with relative geometry to ease changes in orientation, `ZoneVentilation:WindAndStackOpenArea` objects define theirs independently. Thus, a script firstly tagged the base IDFs to account the original orientation of each object. Afterwards, the main one populated and labelled combinations according to the characteristics of the simulation and tags.

Output managers: These scripts managed the output and sanity routines. Each simulation resulted in eighteen files (subtotal= 158 MB), giving a total of 62 208 files and ≈ 530 GB per location. To ease operation and improve runtime of their analysis, they were classified in HDF5, a hierarchical data format especially suited for these applications and common in research. As a preliminary integrity check, a set of functions parsed the E+ error files to ensure they did not have technical problems.

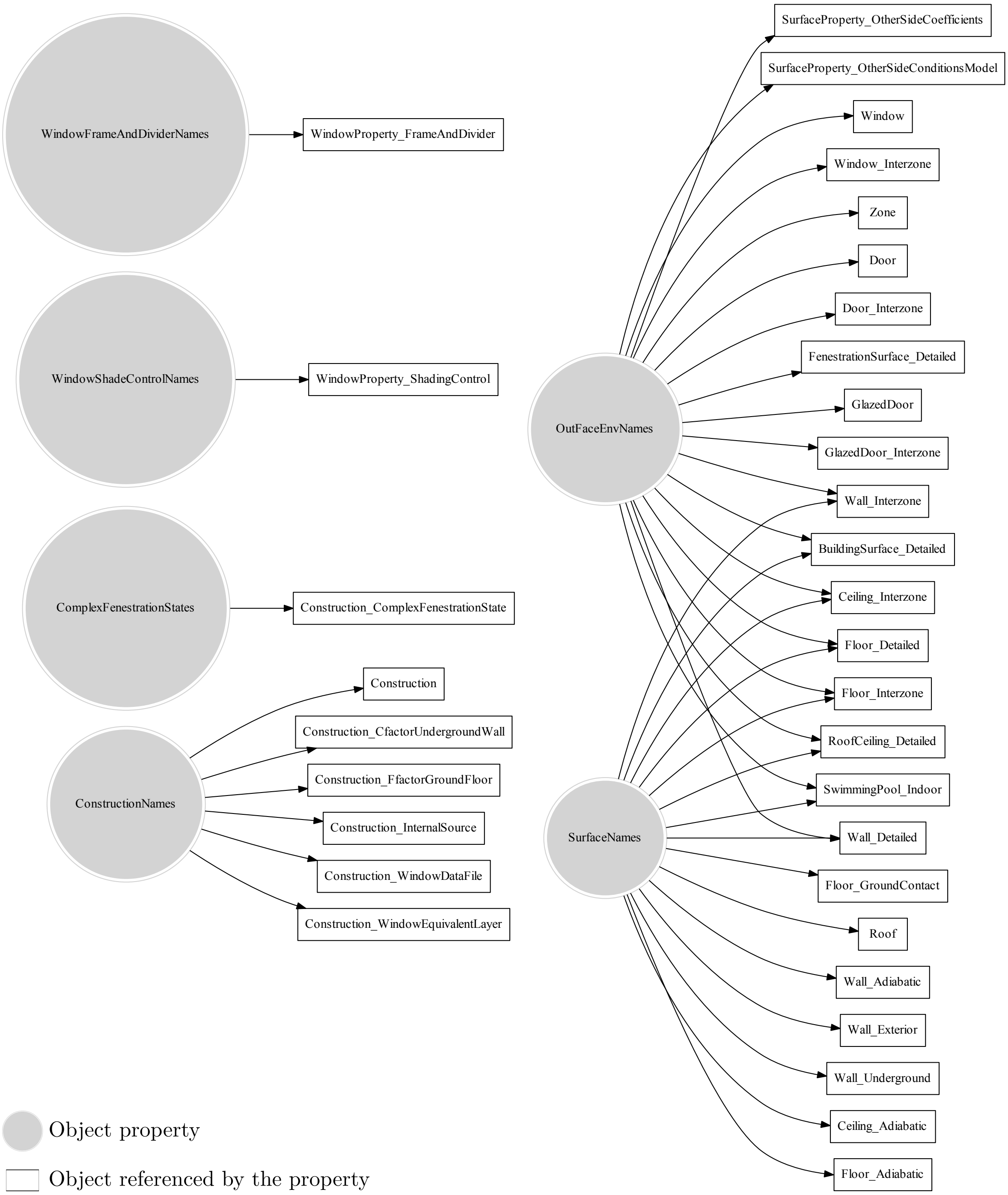


Figure 4.6: `plotMap()` output for E+ `FenestrationSurface:Detailed`

Analysis: Overheating indicators were calculated for each simulation and saved through these routines. Then, they were analysed according to the aims of the project.

4.6 Validation

4.6.1 Simulation

As discussed in section 4.1, it is important to validate simulations to a feasible extent; moreover if the intention is to predict the likelihood of overheating. For obvious reasons, parameter sweep cannot be validated through real cases, as they require combinations unlikely to be found in reality. Overall, the project requires essentially two types of information: temperature in free-running mode and heating energy demand to assess the winter–summer balance.

The house is located next to Southampton, and was developed with high expectations of comfort and low energy demand. Fortunately, this was translated into several independent reports documenting the project at different times and their constant monitoring, including the external environment. The house is CSH Level 4 (it did not reach level 5 due to renewables), claiming to be based on PH principles, as mentioned previously. Despite the 0.12–0.15 $\mathrm{W\,m^{-2}\,K^{-1}}$ transmittances for the opaque envelope, windows and airtightness do not meet PH criteria as they reached values of 1.20 $\mathrm{W\,m^{-2}\,K^{-1}}$ and 1.25 ach@50Pa, respectively. Values from the National Calculation Method or building regulations of that time were used to fill in data not present in the documentation, together with estimations of occupancy based on CO_2 sensors and electricity consumption.

The crucial aspect was the generation of the real weather file. On-site, two groups of sensors take readings for the dry bulb temperature and relative humidity for which the analysis showed significant variations on the daily peaks. Real reasons for these could not be worked out[5]. Nonetheless, this could be cross-checked through MIDAS (Met Office 2015a) as there were several weather stations nearby with congruent readings among them. Additionally, they also had values for additional parameters like wind speed and wind direction. However, the breakdown of solar radiation is not included in this database. Following Met Office suggestions, these were taken from the readings in Camborne ($\approx$ 250 km away), one of the two locations in the UK where this kind of data is recorded in full (Met Office 2015b). Available through the World Radiation Data Centre (WMO 2015), this data was used to inform and derive these values. Missing readings in any of these databases were filled in interpolating surrounding ones and the rest of parameters were based on the London weather file so simulations could be lunched. Internal sensors had problems as well, but these were fully reported by the crew in charge of the monitoring. Hence, periods with missing values were filtered out from the analysis. The weather file was analysed in E+ to derive statistically significant periods for the summer which, fortunately, overlapped with non-problematic periods. An extract of this process is shown in fig. 4.7.

Specific thresholds to appraise the success or failure of the validation could not be located. To derive a meaningful metric, norms were taken (eq. (4.9)). The 2-norm of the difference between the signals was used as the indicator of the average dissimilitude, which, divided by that of the real signal, resulted in 2.4 % ($\approx$ 0.6 K). Similarly, the ∞-norm was taken as an indicator of the dissimilitude of the peaks, being 6.1 % ($\approx$ 1.6 K). As an example to contextualize these values, Csaky and Kalmar (2015), appraising the influence of thermal mass, ventilation and glazing on indoor temperature, arrived at 0.26–0.89 K in *laboratory conditions*. Given the number of uncertainties, simplifications and assumptions in the process, especially for occupancy and behaviour, these have been interpreted as a reasonable guarantee of the validity of the simulation. Still, they represent high proportions of meaningful thresholds

[5] Among possible explanations, it is speculated that their locations might not adequate, being influenced by the temperature of surrounding surfaces.

in overheating (1–4 K). Unavoidably, this leads to appraise the relative changes between simulations rather than absolute values.

$$\|\mathbf{x}\|_p = \left(\sum_{i=1}^{n} |x_i|^p \right)^{1/p} \tag{4.9}$$

Regarding energy demand, this information was available through a number of publications, which have gathered typical ranges according to dwelling types and age of construction. Moreover, FEES and PH establish precise goals. Altogether, this information was used to contextualize the results of parameter sweeps. Since the values obtained are of interest for the hypothesis that addresses annual energy demand, the results are directly discussed in section 5.5.

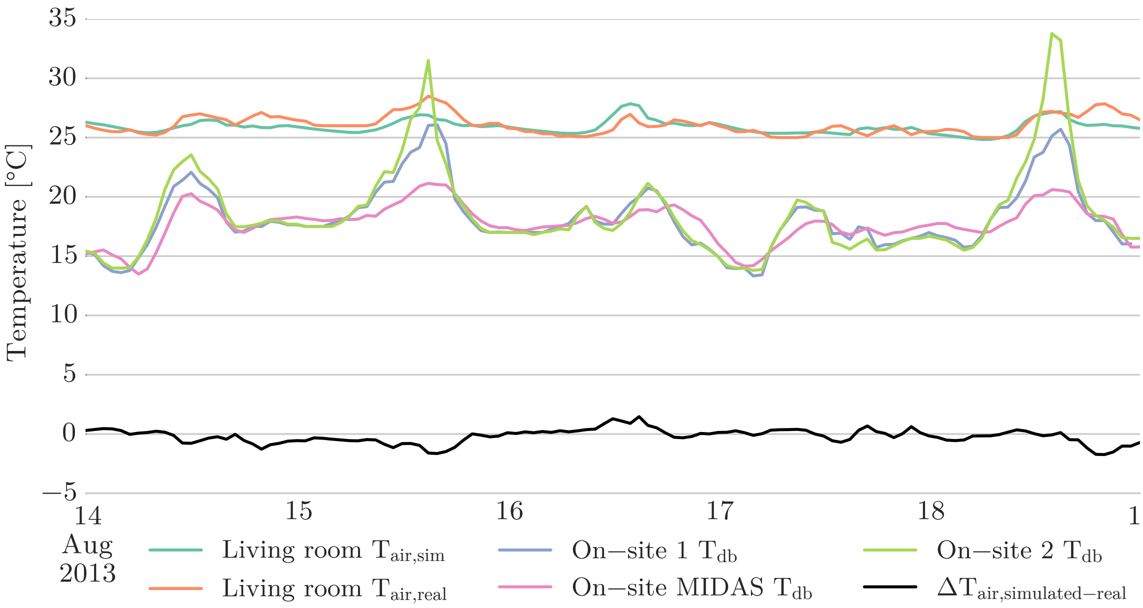


Figure 4.7: Validation of the overheating model: typical summer week

4.6.2 IDF and code

E+ establishes acceptable ranges for object properties and a number of routines in the engine to flag unacceptable or suspicious values during warm-up, sizing and simulation phases. Hence, it can issue warnings to inform how values deviate from what is expected (e.g. override the volume of a zone) or if objects in the simulation were unused, among other features. These were used, together with the real validation, to inform the process, being this type reports analysed after each batch simulation.

The project largely relied on Python scripts. Here, techniques were taken from usual practices in computer science, basically auditing them with `lint` and following good-practice codes, like `pep8`. To ensure their functionality a number of tests were performed. An example of these is shown in listing 1. `diff` was used to compare differences between two files, particularly useful when defining and expanding the split IDF. The extract shows this for the definition of the external wall layers between high and low thermal mass for 1995, where it can be seen how only relevant layers change accordingly to the rules established (red and green, respectively; insulation was adapted correspondingly to changes in other layers, as explained previously).

```
--- (...)\2-C-1995-TM-H.idf
+++ (...)\2-C-1995-TM-L.idf
@@ -1,4 +1,3 @@
-! Description: Construction '1995', Thermal Mass 'High'
 !-Generator IDFEditor 1.44
 !-Option SortedOrder UseSpecialFormat

(...)

@@ -181,22 +203,24 @@
 Construction,
     Exterior Wall,            !- Name
     020_Brick_slips,          !- Outside Layer
-    I:W:1995:H,               !- Layer 2
-    100_Brick,                !- Layer 3
-    015_Plaster;              !- Layer 4
+    I:W:1995:L,               !- Layer 2
+    050_Mineral_Wool,         !- Layer 3
+    010_Plasterboard;         !- Layer 4
```

Listing 1: Comparison of two alternative E+ `Construction` descriptions through `diff`

CHAPTER 5

Analysis and discussion: current weather

This chapter presents the results and discussion altogether due to the interrelationship of the physical phenomena between the three objectives. Firstly, the locations are introduced to set the context of the results and to allow easier interpretation of what is happening between them. Then, the methodology of analysis is discussed according to its suitability to answer the hypotheses. Each of the next three sections address their corresponding objective following these indicators:

1. **Independent overheating characterization:**
    a) **Duration:** Hour count.
    b) **Severity:**
        i. Temperature profile.
        ii. Breakdown of hours according to temperature bins.
    c) **Discomfort:** PPD-weighted occupied.
2. **Specific overheating criteria:** TM-36, TM-52 and PH.
3. **Energy demand balance:** Heating energy demand and Cooling Degree-Hours (CDH).

5.1 Locations

As mentioned in section 4.3.10, simulations covered London, Manchester and Edinburgh to have an approximation to the overall performance in the UK. The overview of the temperatures shows how they evolve throughout the year, following the expected trends according to their latitudes (fig. 5.1). In London, they reach their peak in June whereas Manchester has them in July and Edinburgh in August. From their values, it is seen how overheating risk should be higher for London, especially when contextualized with their comfort thresholds (figs. 4.4 to 4.5, figs. B.1 to B.2 figs. B.3 to B.4). Manchester would be second, but here the interest resides on how the daily swings will affect the risk, significantly higher in this place.

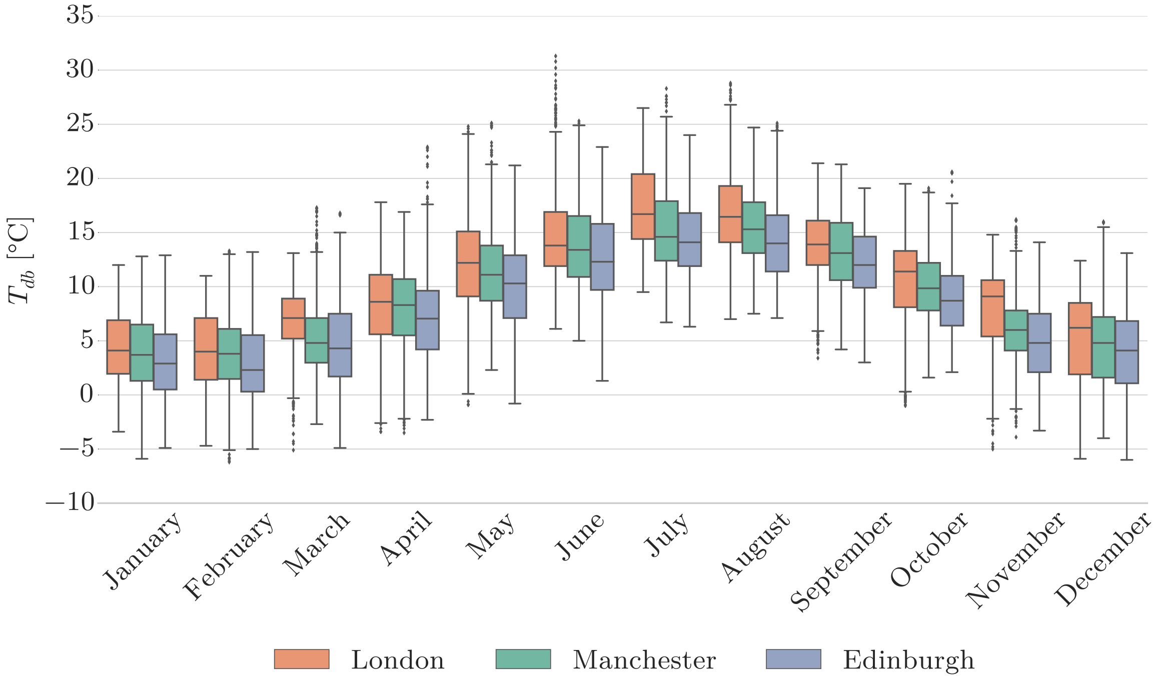


Figure 5.1: Dry bulb temperature summary for the locations

5.2 Methodology

The main variables of interest for this study are the changes in building fabric and location. Thus, results will be presented taking these parameters as the drivers of the analysis. The focus has been placed on the living room, the kitchen and the three bedrooms leaving the rest out of the scope of the discussion. The annual summary of performance leads to 3456 simulation · 5 rooms/location values per indicator, which translates into 4320 individual readings when split by the main variables of interest. Figure 5.2 illustrates what this entails in the case of the hour count indicator. Visualizing the performance of each simulation and room allows seeing broad changes between locations and constructions, but collapsing every other parameter leads to significant dispersions since they were defined with low-high extremes. As a result, it is difficult to extract more information beyond the increased density towards lower values.

The summary statistics[1] in table 5.1 clearly shows the trends between different standards, where the hours in discomfort increase as the building fabric is improved. As hinted by the graph, their standard deviation is extremely significant and the coefficient of variation ranges about two to three times the mean. The main cause for this dispersion can be tracked down to ventilation strategies. As mentioned in section 4.3.8, three scenarios were considered to bound the performance due to the lack of knowledge regarding occupant behaviour and the technical limitations of current natural ventilation models. The theoretical scenario where purge ventilation is forbidden has an obvious impact on the risk, which largely masks the effect of other strategies and parameters. Thus, ventilation strategies were taken out as a parameter

[1] For convenience, the mean and standard deviation are computed using the Bayesian approach presented in Oliphant (2006). The 95% Bayesian Credible Interval (CI) was included to illustrate what would be its range if the large amount of data was taken as random.

to present findings, which have resulted in the adaptation of the Y-axis scale to show the meaningful range. When this happens, a warning is issued in the caption of the figure for clarity. A second characteristic shown in the figure and the tables is that the distribution is squeezed towards lower values. Otherwise, taking into account the mean and the standard deviation, hours would be negative if a normal distribution was assumed. This is expected for this indicator because the lowest value possible is zero, being noticeable the increase in density there in the figure.

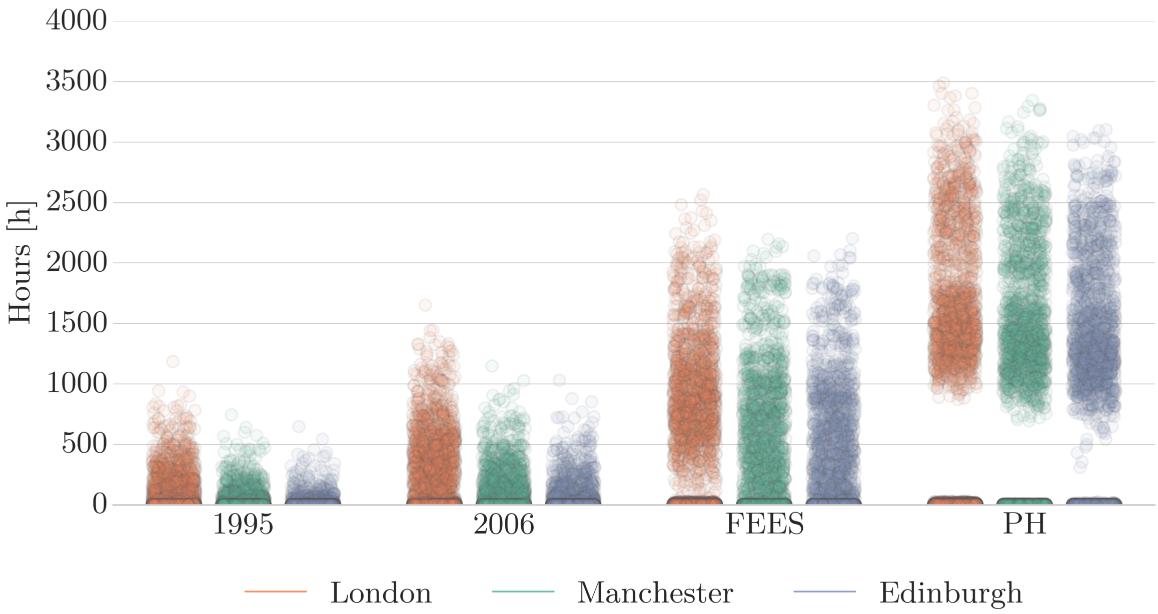


Figure 5.2: Duration (indicator 1-1): Overall hours above ACM $T_{cm,max}$

	1995		2006		FEES		PH	
μ	49.85	±3.53	129.47	±7.28	320.43	±15.52	591.54	±26.63
σ	118.42	±2.50	244.15	±5.15	520.43	±10.97	892.95	±18.83

(a) London

	1995		2006		FEES		PH	
μ	18.30	±1.68	47.11	±3.58	212.47	±12.47	534.97	±24.37
σ	56.43	±1.19	120.05	±2.53	418.23	±8.82	817.28	±17.23

(b) Manchester

	1995		2006		FEES		PH	
μ	7.78	±1.07	25.01	±2.47	176.90	±11.19	502.57	±23.01
σ	35.92	±0.76	82.77	±1.75	375.39	±7.92	771.53	±16.27

(c) Edinburgh

Table 5.1: Overall hours above ACM $T_{cm,max}$

These considerations have led to an analysis based on the summary of indicators through their mean, standard deviation and distribution. Of these, the mean will constitute the leading one because the interest of the study is on trends, easily appreciated through its plot. This is particularly suitable because the study can rely on pairwise comparisons due to the way simulations were generated and the extraction of co-dependent parameters in different groups (age of construction, ventilation). Yet, the clarity achieved is at the cost of meaning in the precise absolute value because it collapses all other parameters and, for instance, rooms with very different occupancies in the case of the hour count indicator. Therefore, tables with the summary statistics will provide the context within which consider the plotted values. Lastly, boxplots will offer a general overview of the distribution[2]. For this task, histograms are usually more suited, but given the dispersion and the amount of data, they can be misleading depending on the number of bins. Other techniques as kernel density estimation were especially suited, but they were computationally intensive and the output would have been verbose for what was required. Since trends of pairwise comparisons constitute proof to test the hypotheses, the last two have been often located in the appendix for brevity.

5.3 Independent characterization

5.3.1 Duration

The most basic overheating indicator is the hour count in which standards build up their criterions. The breakdown according to ventilation strategies in fig. 5.3 depicts a different scenario than that previewed in fig. 5.2. At general level, it can be appreciated how the duration varies as expected, including the change in location. For the case when purge ventilation is not allowed, the conclusion remains the same as before: moving from 1995 —taken as the base case— the risk increases when the building fabric is improved. Yet, if occupants are allowed to open the windows during daytime —as per ACM theory— the risk is more stable between constructions.

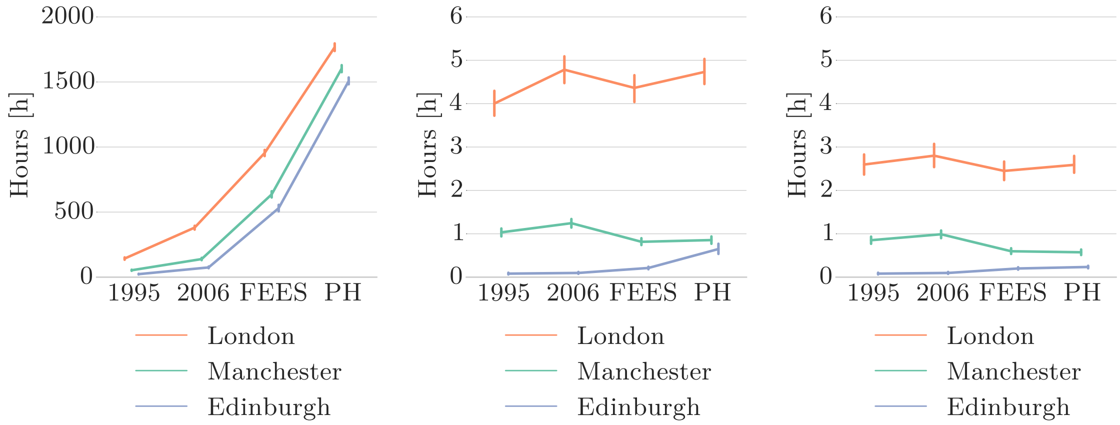
For London, the risk increases when compared to 1995, but the relative change is much smaller, decreasing locally for FEES. Nighttime purge further lowers absolute values for it by about 30–50 % when compared to the previous. Here, the behaviour considered maximizes the temperatures to the colder threshold, taking advantage of the thermal mass of the medium and heavyweight scenarios (TMP of 280 and 520, respectively). Interestingly, Manchester depicts a different trend, shifting for FEES and PH when purge is available, whereas in Edinburgh it keeps increasing.

Table 5.2[3] further explicit the values achieved and the benefits of this breakdown. The mean value of 1995 for London in table 5.1 was 50, whereas here is split into 143, 4 and 2.6, approximately. Thus, it is quantified how the risk is worsen in the first scenario, whereas is within the same magnitude for the latter two. In addition, the standard deviation has dropped significantly. Further benefits can be obtained if the breakdown is expanded to other parameters as well —e.g. occupancy profiles, shading, glazing ratio— but this would make the assessment unnecessarily more complex for the purposes of this study (more on this in section 5.3.4).

To explore these changes in overheating, it is convenient to look at hourly data to understand the mechanisms that trigger the different behaviours. London is taken as the

[2] Outliers were not included so they do not prevent general understanding: under extreme cases, like no shading and high glazing ratio for cases with forbidden purge, their number increase significantly.

[3] Complete description in appendix C.



(a) Purge: None (b) Purge: Day (c) Purge: Night

Figure 5.3: Duration (indicator 1-1): Average hours above ACM $T_{cm,max}$ (Note: Y axis scale adapted for *Purge: None*, CI:95%)

	1995		2006		FEES		PH	
μ	142.96	±8.80	380.84	±14.97	954.47	±23.64	1767.30	±29.14
σ	170.34	±6.22	289.80	±10.58	457.68	±16.72	564.28	±20.61

(a) Purge: None

	1995		2006		FEES		PH	
μ	4.00	±0.29	4.78	±0.32	4.36	±0.29	4.73	±0.29
σ	5.60	±0.20	6.13	±0.22	5.59	±0.20	5.62	±0.21

(b) Purge: Day

	1995		2006		FEES		PH	
μ	2.60	±0.25	2.80	±0.26	2.45	±0.21	2.59	±0.19
σ	4.79	±0.18	4.96	±0.18	4.02	±0.15	3.65	±0.13

(c) Purge: Night

Table 5.2: Duration (indicator 1-1): London average hours above ACM $T_{cm,max}$ (CI:95%)

main case because of the higher risk and, to make variations more clear, a 1995 dwelling will be compared to its equivalent in PH. The differences between constructions are only due to insulation, airtightness and ventilation systems since other parameters are collapsed under the pairwise comparison. At the same time, these three are the main responsible for the cooling since there is no other mean available.

Previous data has shown a steep increase in risk when purge ventilation is not allowed, being the duration in PH dwellings about twelve times that of 1995 ones. However, when daytime purge is available the increase is 18%. Figure 5.4 shows the evolution of temperatures in the hottest day of the TRY weather file for a combination with significant overheating risk —high glazing ratio and lack of shading devices— when purge is available during the day. The scenario with three occupants all-day-long home has been taken to simplify the discussion of other parameters such as internal gains or availability to open or close windows. The discussion starts with daytime purge as a reference for the neutrality temperature of that day since this opening behaviour aims at maximizing comfort, whereas the nighttime one seeks further cooling (figs. 4.4 and 4.5).

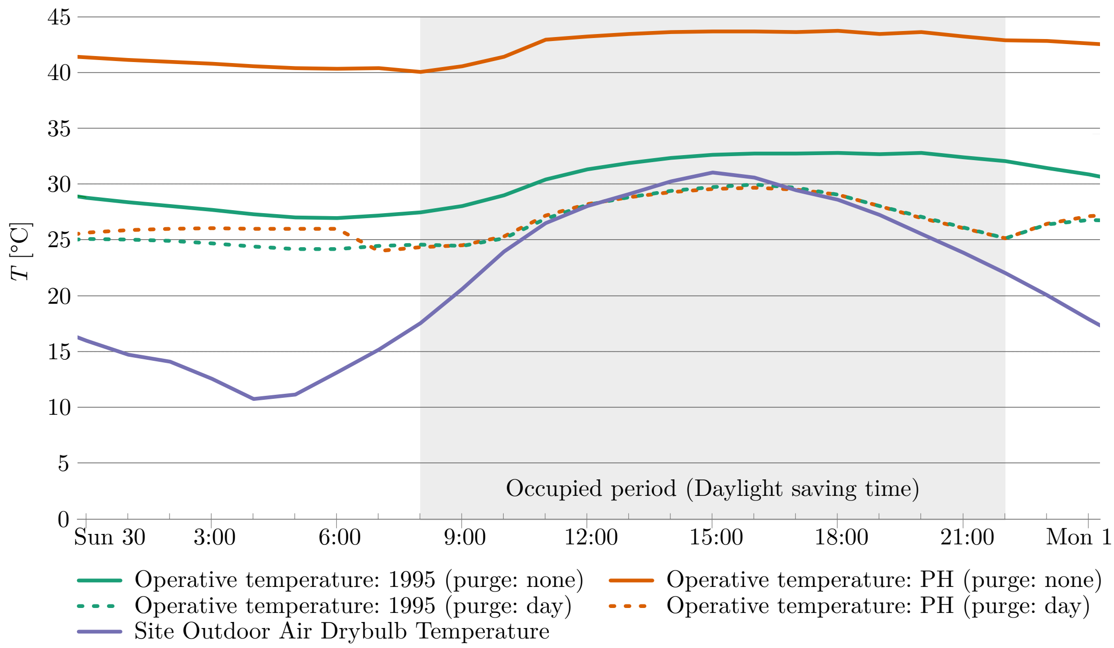


Figure 5.4: Simulation hourly evolution of the living room in the hottest day 1/2 (Location: London, Thermal mass: Medium, Glazing: High, Shading: Urban, Gains: 3p, Infiltration: High, Orientation: South)

When occupants wake up at 07:00h purge is available and the temperatures of 1995 and PH are virtually the same, 24.5 °C. This can be achieved since the external one is colder but, later in the day, its rise makes undesirable to keep windows open. Thus, the comfort threshold is surpassed because no other mean of cooling is available. Temperatures start to drop at 17:00h, but those of the living room at a slower pace than the external due to the internal heat gains. At night, windows are shut and the temperature rises because the thermal mass is warmer. Here, the temperatures of 1995 and PH start to diverge. The combination of the background ventilation and the higher infiltration gains keeps lowering the temperature in 1995, whereas in the PH they remain sensibly constant.

When purge is not available, the internal temperatures are consequently higher. Their profiles follow the same trends, but they are significantly flattened because of the thermal mass and the lack of purge ventilation. The combined effect of insulation, infiltration and ventilation keeps the PH about 10 °C warmer than the 1995 dwelling, accounting for the deep increase in overheating duration. PH reports higher values not only during the whole occupied period, but also for a larger fraction of the year, since this increase surpasses the maximum comfort temperatures from March to November, whereas 1995 does it during the summer. In addition, the offset between no purge and daytime purge of this 1995 case is about the same magnitude of the +3 °C deviation allowed in the EN-15251, which further decreases the amount of time overheating is reported. To see what would have happened if the 1995 dwelling were to have the conditions of the PH except for the insulation, a theoretical case was modelled (fig. 5.5). As seen in the same figure, this accounts for 25–35 % of the temperature increase between 1995 and PH, being the rest due to insulation. More interestingly is to give the PH the airtightness of 1995. The internal temperature drops significantly until a value of +1 °C from 1995 on average, accounting for about 90 % of their difference.

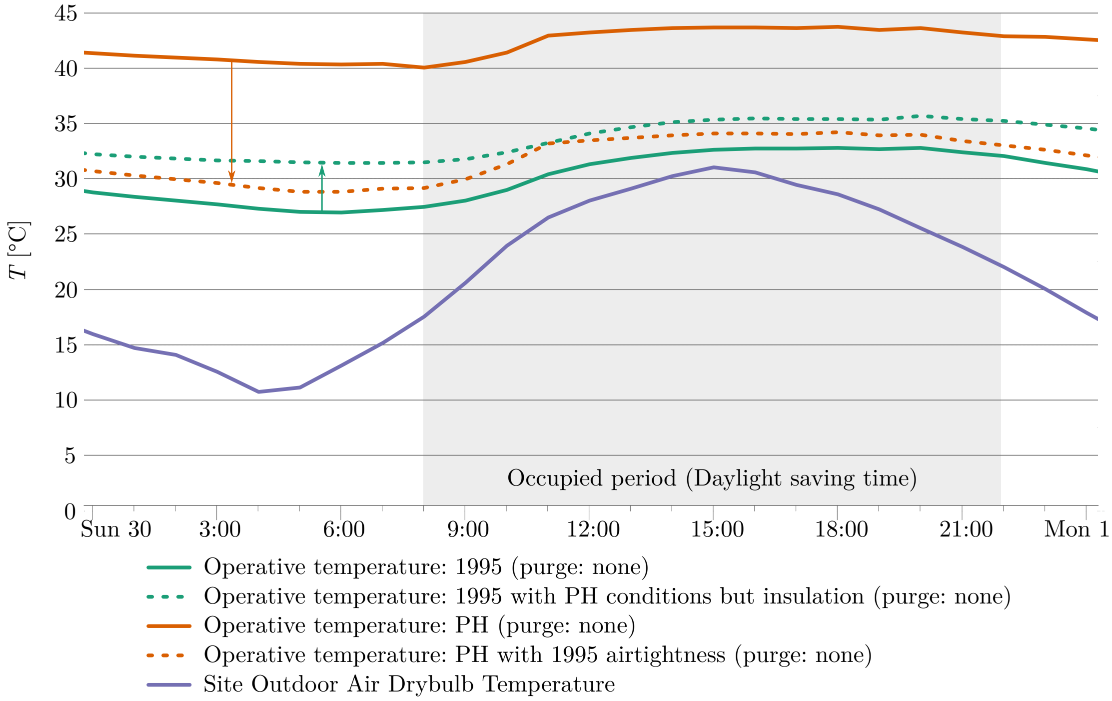


Figure 5.5: Simulation hourly evolution of the living room in the hottest day 2/2 (Location: London, Thermal mass: Medium, Glazing: High, Shading: Urban, Gains: 3p, Infiltration: High, Orientation: South)

On the one hand, the increase in overheating when purge is not available aligns with the studies that identified higher risk when insulation is improved. Logically, the higher the insulation the smaller the heat loss if all other conditions are the same, only possible because external temperatures in the UK are generally lower than the comfort range. As seen in chapter 2, most studies have focused on equivalent qualities of construction (e.g. within retrofit or super-insulated ranges). Here, changes are more pronounced because of the widen scope. However, if a 1995 dwelling is given the conditions of a PH but the insulation, overheating risk changes significantly. The increase in 25–35 % of their difference is enough to report a risk much greater than before, largely due to the new airtightness. Yet, when a PH is given just the infiltration of 1995 the change is a 90% drop.

This illustrates the sensitivity of both cases when considering heat loss through insulation as a cooling strategy, showing that is very ineffective. The moment other means such as greater infiltration are available its role diminishes significantly, being negligible when windows can be opened. This also accounts for the local drop in FEES in daytime purge for London. The relationship between airtightness and insulation is more favourable for overheating than that of PH since air leakage alone is eight times greater in a FEES. Therefore, is normal situations, insulation should be regarded as an efficiency measure, not a cooling mechanism.

One of the recurrent concerns of overheating studies is that ventilation might not be an option due to noise or security issues. This unavoidably raises the risk in every situation, but for a PH to perform closely to 1995 all that is needed is to open them about the equivalent air leakage area or deliver this airflow through the MV unit at the expense of the fan consumption. From this point onwards, the risk between them is very alike or even decreasing for better standards when overheating is significant (London and Manchester).

Lastly, it is worth considering the comparison between 1995 and FEES in Manchester when nighttime purge is available to explain improvements in performance (fig. 5.6). Both dwellings have the same starting point, given by the lower comfort threshold —three degrees under neutrality for EN-15251 Category II—. Thus, the mean radiant temperature is also the same between them during the night. As the external temperature rises, their performance starts to diverge. By the time the peak is achieved, 1995 features a temperature closer to the external than that of the FEES. As soon as the exterior reaches values above comfort, the advantages of less airtightness and insulation in the 1995 dwelling are lost, whereas their improvement in FEES translate into smaller peaks, which is when overheating takes place. This happens for nighttime purge in London and Manchester because they develop more frequently external temperatures over comfort thresholds. For the latter, this behaviour is capable of shifting marginally the trend for daytime purge because it features greater daily swings. It is convenient to remember that overheating is a temperature increment over comfort, achieved in a 6 K band in the category considered. This means that the daily swings in Manchester are large enough in relative terms to record overheating but low in absolute values so the relative increments between 1995–FEES matters.

Overall, it can be seen that the hour count above maximum comfort threshold leads to detailed considerations to make sense of the values achieved. This is because it establishes a fictional threshold to report values: 0.01 K below and no overheating is reported but, when above, it matters as a complete hour. Thermal comfort theory models dissatisfaction as a continuous function and, based on that, categories are established as deviations from neutrality. These are necessary to establish goals of performance but when assessing overheating they can be misleading. The exception would be when temperatures vary significantly, as in the case when purge is forbidden; there the hour count is reliable. The next indicators will offer better perspectives through which evaluate the risk.

5.3.2 Severity

Severity is appraised in two complementary ways: average temperatures and the breakdown of the hour count according to ΔT_o bins. The first provides an overview of the annual performance whereas the second is more specific to overheating risk. These summaries allow appraising the behaviour of different building standards without having to rely in hourly data since it can be questioned to which extent individual simulations represent their groups. Because of the amount of information of these indicators, locations are presented separately and the information regarding standard deviation and distribution omitted for brevity.

Figure 5.7 shows the average temperatures developed in each group. These are the result of computing the minimum, the quartiles and the maximum of all the temperatures in a dwelling, regardless the occupancy. These five values are then averaged with their corresponding ones in other cases to show a representative figure. This way their interpretation is eased since they do not have to be correlated with the presence of occupants for instance, very different

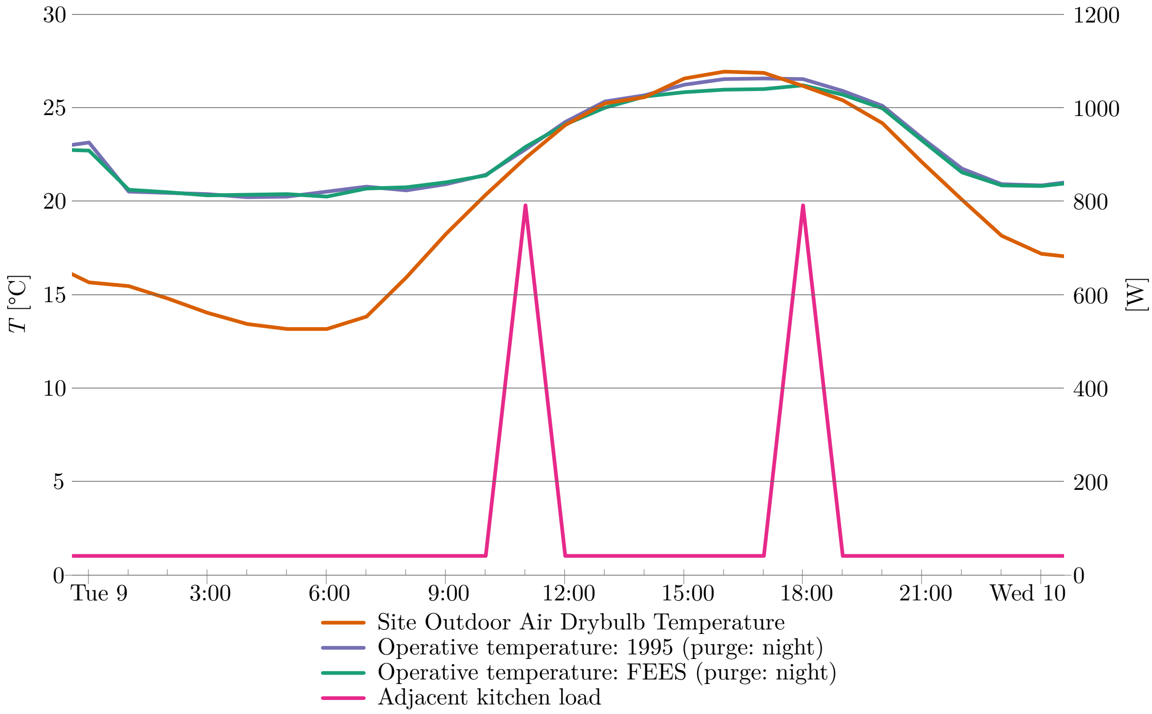


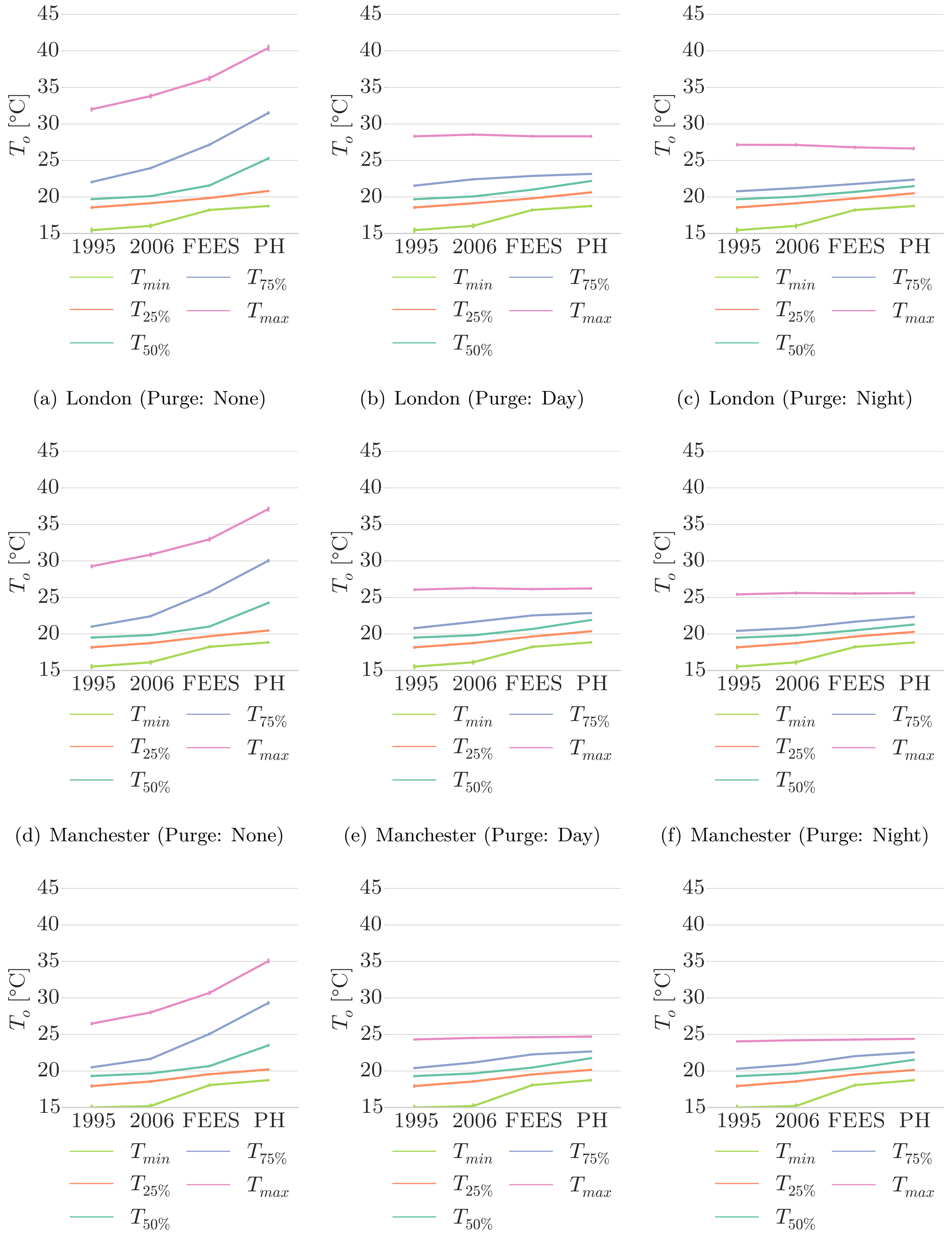
Figure 5.6: Simulation hourly evolution of the living room (Location: Manchester, Thermal mass: Medium, Glazing: High, Shading: Urban, Gains: 3p, Infiltration: High, Orientation: South)

in each of the two scenarios. As a result, it can be seen how the minimum temperature is below the 20 °C explained because heating controls *air* temperatures and because unoccupied periods and rooms are also taken into account.

The general trend depicts performance as expected, with temperatures progressively colder when moving from London to Edinburgh or between the different purge availability scenarios. The minimum and first quartile shows how FEES and PH performs better than 1995 and 2006, with temperatures closer to comfort because of insulation and airtightness. However, when windows cannot be opened, the following quartiles and maximum values show a large increase at standard level and when moving from 1995 to PH. This further explains the values obtained in the hour count and the large increment in risk: $T_{o,75\%}$ is around the comfort range for 1995–2006 but above it for FEES–PH.

Yet, the situation is sensibly different for the other cases. When purge is allowed quartiles keep increasing slightly between constructions because values below the upper comfort limit are encouraged by the opening strategy. The moment overheating is about to be reached they tend to stabilize. Still, in the hour count it was seen how the risk can be lower for FEES and PH in these scenarios. This is because temperatures were averaged regardless of the occupancy. Half of the cases consider that the occupants leave the house from 09:00 to 17:00 (family scenario), leaving windows shut (fig. 5.8).

The nighttime purge temperatures of 1995 and PH are the same at the beginning of the day and the thermal mass is as cool as comfort allowed. When occupants leave the house, the room starts to heat up according to the external environment. The evolution of the internal temperatures is at a slower pace because of the insulation and the stored heat. As seen before,



(a) London (Purge: None) (b) London (Purge: Day) (c) London (Purge: Night)

(d) Manchester (Purge: None) (e) Manchester (Purge: Day) (f) Manchester (Purge: Night)

(g) Edinburgh (Purge: None) (h) Edinburgh (Purge: Day) (i) Edinburgh (Purge: Night)

Figure 5.7: Severity (indicator 1-2): Average internal temperature (CI:95%)

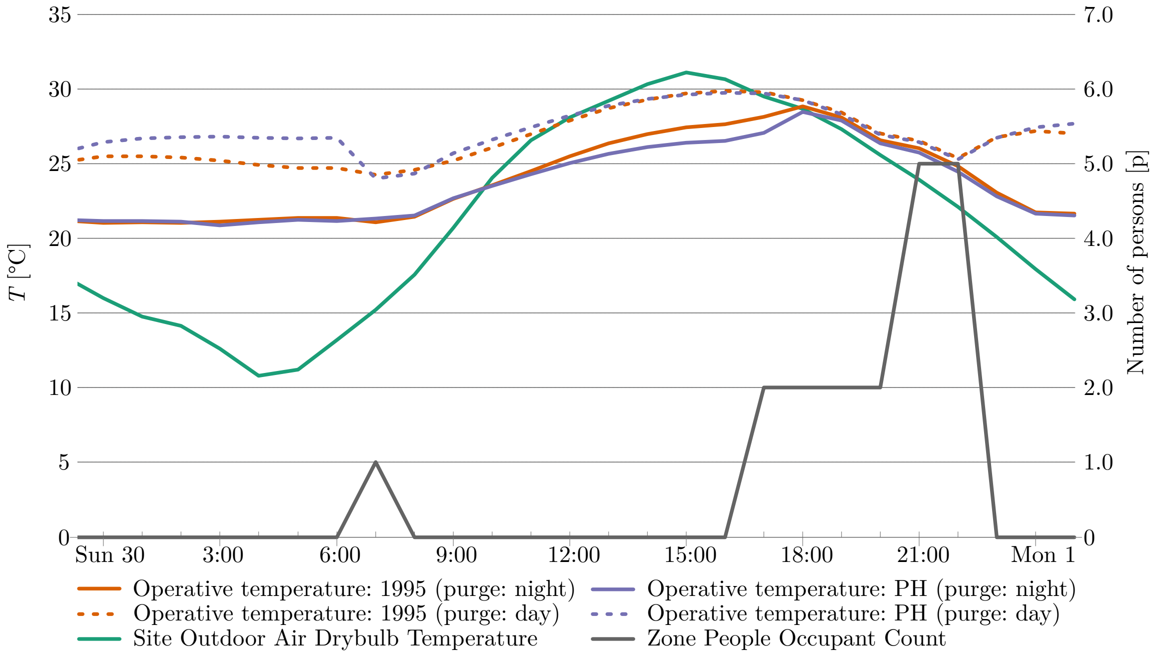


Figure 5.8: Simulation hourly evolution of the living room (Location: London, Thermal mass: Medium, Glazing: High, Shading: Urban, Gains: 5p, Infiltration: High, Orientation: South)

PH outperforms the 1995 dwelling due to greater airtightness and insulation levels but, in the case of daytime purge, the difference is barely noticeable inasmuch as the PH has its thermal mass warmer than in 1995. It cannot cool it during the night as a result of greater airtightness and restricted purge.

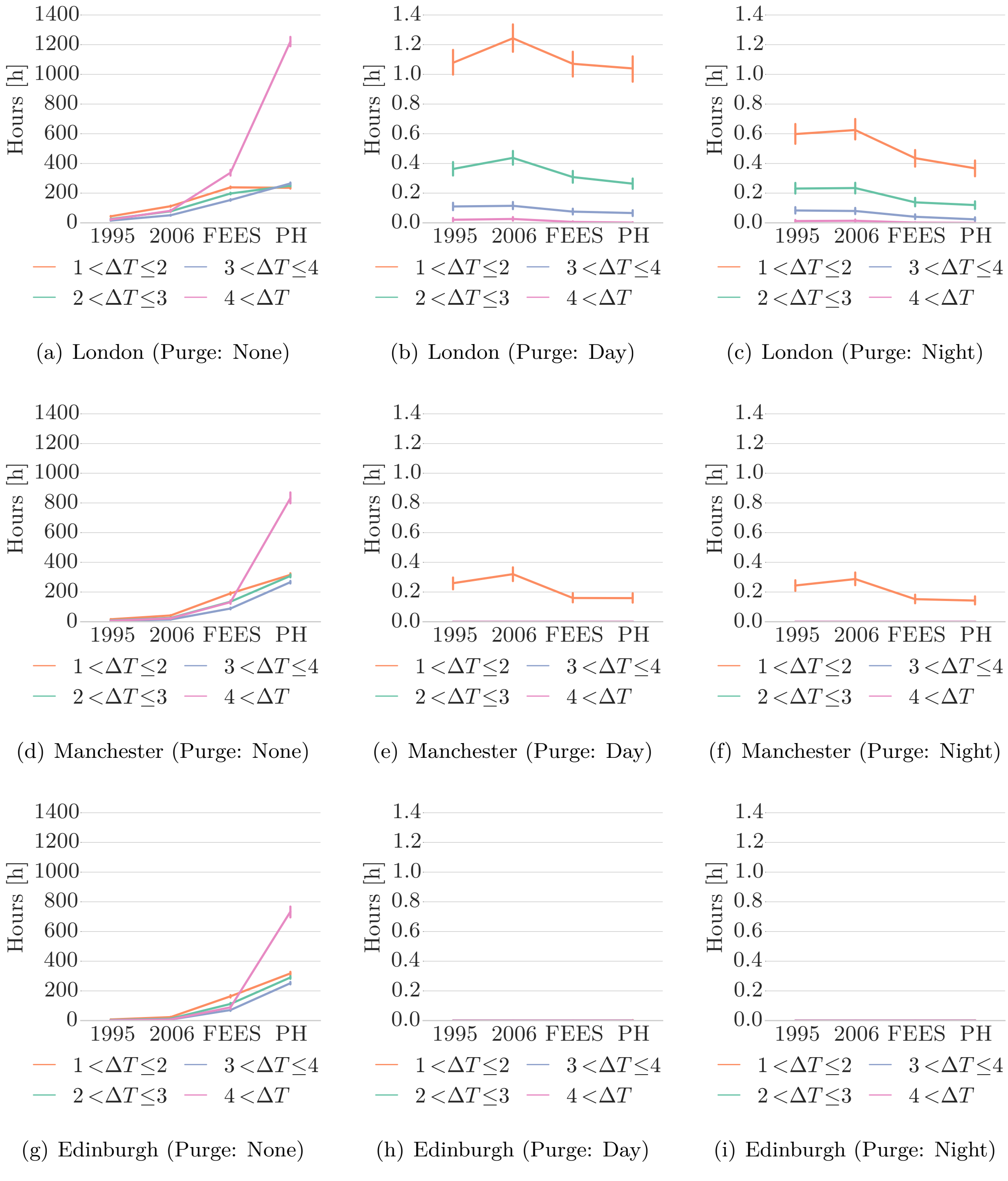
Figure 5.9 decomposes the hour count according to severity. The bin between cero and one has been omitted for clarity and because is not representative of serious overheating risk[4] —even the TM-52 disregards it—. These graphs show not only that the risk in Manchester and Edinburgh is anecdotic, but also that improved building fabric reduces the severity of overheating when occupants are allowed to open windows. Where they cannot, dwellings tend to develop temperatures much higher than the upper comfort threshold as seen before. Altogether, this supports the explanations given in the previous section, proving that the conclusions and hourly insights are representative.

5.3.3 Discomfort

To assess discomfort with a single indicator, the PPD-weighting was preferred over the traditional degree hour because of consistency with thermal comfort theory, but this only adjusts the specific absolute value (fig. 5.10 and table 5.3)[5]. In any case, they would have identified the same *trends* since the method of counting hours does not change and the weights in both cases are strictly increasing functions. It features the same limitations as the simple hour count regarding the threshold and the noise of the first bin —between cero and one—

[4]However, its value can be obtained comparing this to fig. 5.3.

[5]Complete description in appendix C.



(a) London (Purge: None) (b) London (Purge: Day) (c) London (Purge: Night)

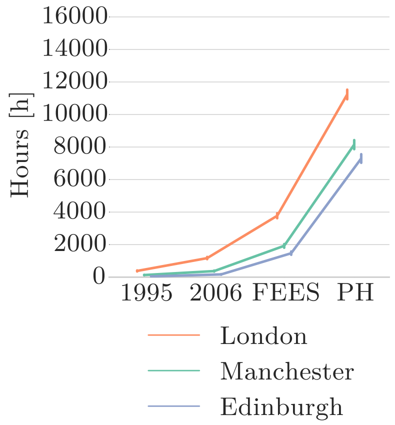
(d) Manchester (Purge: None) (e) Manchester (Purge: Day) (f) Manchester (Purge: Night)

(g) Edinburgh (Purge: None) (h) Edinburgh (Purge: Day) (i) Edinburgh (Purge: Night)

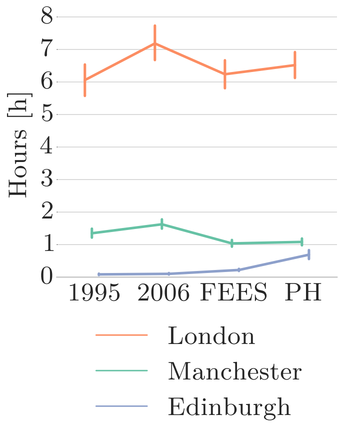
Figure 5.9: Severity (indicator 1-2): Average hours breakdown for ΔT above ACM $T_{cm,max}$ (Note: Y axis scales adapted for *Purge: None*, CI:95%)

would have been reduced if it were not for the fact that it represents a significant portion of overheating when purge is available.

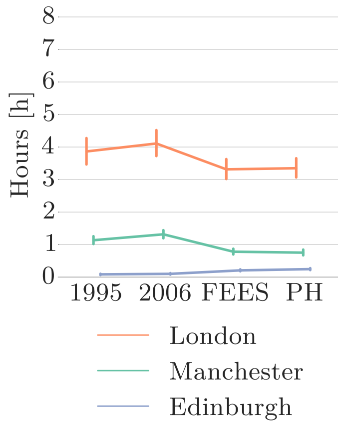
The impact, when compared to fig. 5.3, is the change in the absolute value. When purge is not allowed, London reports ten times the previous risk, recognizing the severity seen in the previous indicator, whereas the others have increases about 50%. The risk for other locations remains essentially the same because theirs took place for very low ΔT. Since discomfort



(a) Purge: None



(b) Purge: Day



(c) Purge: Night

Figure 5.10: Discomfort (indicator 1-3): Average PPD-weighted hours above ACM $T_{cm,max}$ (Note: Y axis scale adapted for *Purge: None*, CI:95%)

	1995		2006		FEES		PH	
μ	383.21	±32.37	1170.33	±68.06	3773.70	±159.30	11 234.67	±304.98
σ	626.63	±22.89	1317.80	±48.13	3084.20	±112.64	5904.85	±215.66

(a) Purge: None

	1995		2006		FEES		PH	
μ	6.06	±0.48	7.18	±0.52	6.24	±0.45	6.52	±0.44
σ	9.28	±0.34	10.08	±0.37	8.67	±0.32	8.43	±0.31

(b) Purge: Day

	1995		2006		FEES		PH	
μ	3.86	±0.41	4.11	±0.42	3.31	±0.32	3.35	±0.28
σ	7.89	±0.29	8.11	±0.30	6.19	±0.23	5.49	±0.20

(c) Purge: Night

Table 5.3: Discomfort (indicator 1-3): London average PPD-weighted hours above ACM $T_{cm,max}$ (CI:95%)

grows exponentially, it is of interest to see the maximum values (fig. 5.11). The graph clearly quantifies how better standards achieves greater satisfaction when windows can be operated.

Finally, it can also be observed that in several indicators 2006 performed worse than 1995 for daytime purge. This is due to the relationship between better insulation and reduced airtightness since they share the same ventilation system. In this case, the thermal mass of the building tends to have higher temperature because of the lower airtightness, being closer to the threshold as occurred in the PH. When the external temperature reaches its maximum the air leakage is still significant and the insulation has not been improved as much as in FEES, resulting in marginally worse performance than 1995.

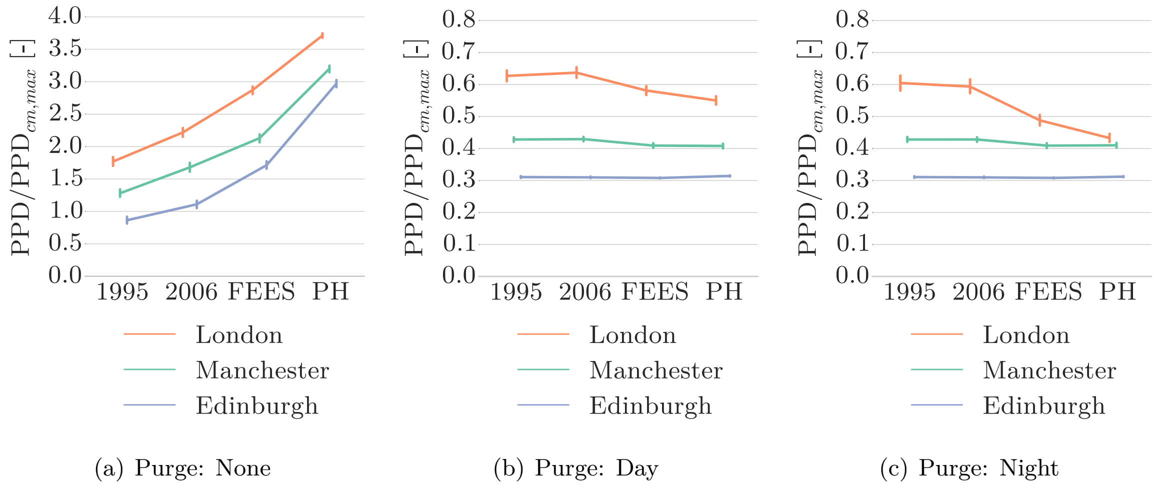


Figure 5.11: Discomfort (indicator 1-3): PPD over $\mathrm{PPD_{cm,max}}$ (Note: Y axis scale adapted for *Purge: None*, CI:95%)

5.3.4 Insights: London

Despite the appropriateness of the mean to summarize the trends in pairwise comparisons, it has been observed that its precise value is of little use when contextualized with the standard deviation. Grouping by locations, purge strategy and standard of construction provides enough information to address the general performance while removes the collinearity of the parameters that were defined as a function of the building fabric. However, it does not translate into real understanding of what is happening within each group when taking into consideration the others.

In order to approach this, insights of how the risk varies according to them is discussed here. The results are presented split by occupancy and room because of two reasons. Firstly, the approach with two occupancy scenarios was meant to capture very different situations which, in addition, entails changes in how purge ventilation is operated, removing the remaining collinearity for the breakdown. Secondly, indicators are only relevant for spaces that are occupied. This accounts for a significant fraction of the standard deviation as the pairwise comparison was mixing, for instance, the living room, the main bedroom, and the kitchen, each of which has very different occupancies and risk. The breakdown is shown for the case of London with purge available during daytime because this is the more balanced among the three and it satisfies the premises of the ACMs as well. This should be done with the ΔT, but this would make the assessment more complex due to the quantity of data. Instead, the PPD-weighted overheating hours is preferred for brevity. This procedure does not have to reduce the standard deviation necessarily because only one parameter at a time is extracted. There are statistical techniques to reduce the number of dimensions of the data, which, for instance, can rank parameters according to their importance, but these fall out of the scope of the project and are well known. In addition, those results are often meaningful at statistical level, separating from the physical phenomena.

Thermal mass works as expected, following the behaviour already hinted in the literature review: lightweight constructions greatly increases the risk, although here it is not a feature of greater insulation (fig. 5.12). For low thermal mass, the heat gains are translated instantaneously in raising the internal temperature. This is better seen when comparing the five-person scenario (family) to the three-person one (pensioners). In the latter, there is always someone in the living room, reason why a greater amount of hours is reported. It is also important to notice that the breakdown shows a reasonable amount of hours when compared to that of the mean in previous indicators. The low thermal mass greatly hinders the overheating performance because solar gains directly affect the occupants whereas for the family they take place during unoccupied hours . Where the mass is relevant, gains use up the stored energy. Bedrooms perform according to their occupancy but the kitchen still reports very high values considering the hours it is being used since cooking largely rises its internal temperature. Lastly, it should be noted that the risk is not symmetrical between cases, not satisfying the prediction of the SAP assessment (fig. 4.2).

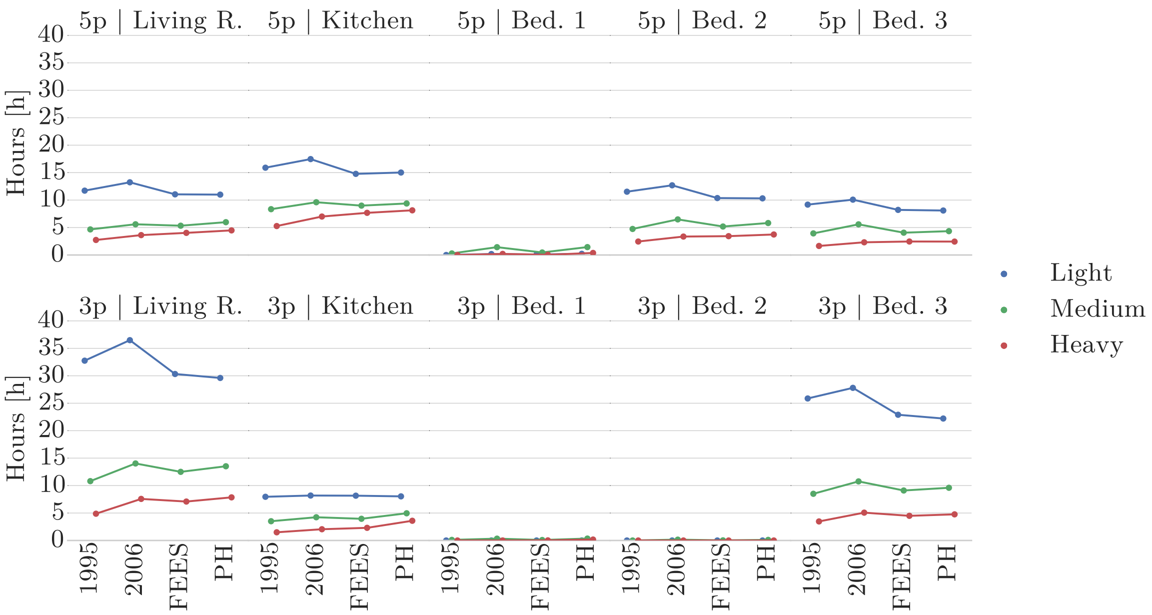


Figure 5.12: London (daytime purge) PPD-weighted average hours: thermal mass

Changes to the glazing ratio perform exactly as foreseen (fig. 5.14). The risk is sensibly symmetrical to the medium scenario because modifications were modelled to keep their shading conditions and were based on the window-to-floor glazing ratio metric. Shading is very similar to glazing, where it is remarkable that the change from unshaded (just the urban environment) to fully shaded is roughly the same as moving from low to high glazing (16 to 26%). However, the year-round performance is obviously not the same due to the U-value of openings. In both cases, the importance diminishes for the family as they are away when the peak solar gains take place.

The role of infiltration is negligible when appraising it according to constructions, even more so when purge is available (fig. 5.13). The only aspect worth mentioning is that the low–high scenarios tend to the same value as building fabric is improved. The ratio of the change is maintained in every case but the absolute values are progressively smaller, reporting virtually the same one for PH.

In the case of orientations, their ranking is essentially a function of the occupancy because every room has the same one, except for the kitchen (fig. 5.16). Thus, in the case of pensioners, west and south are the most unfavourable ones because the sunrays reach the room in the

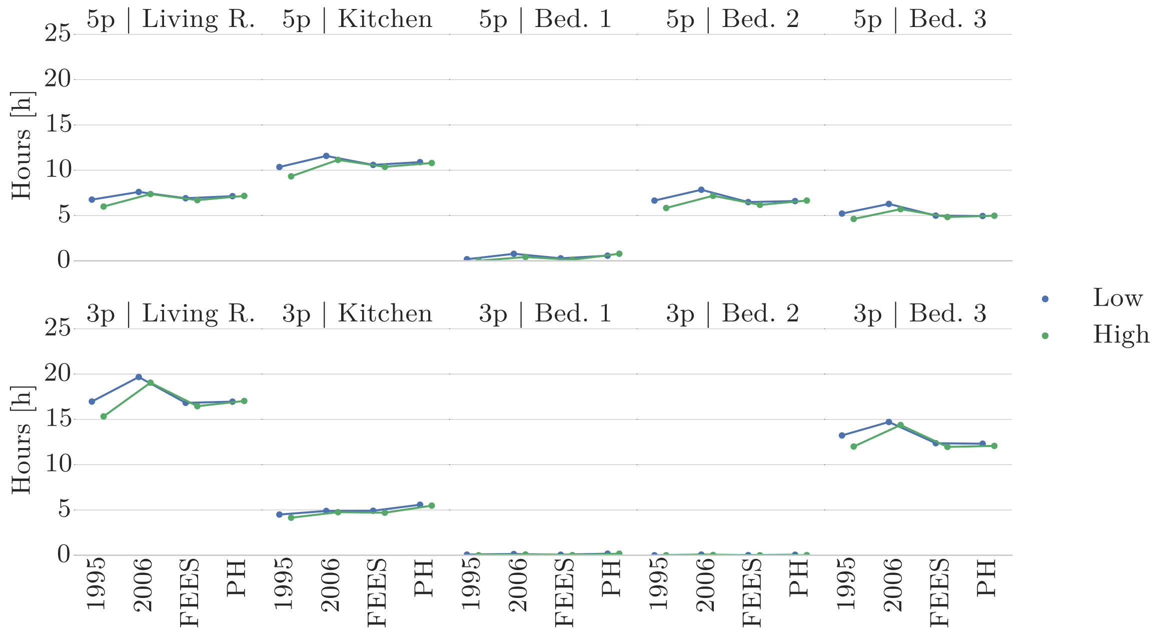


Figure 5.13: London (daytime purge) PPD-weighted average hours: infiltration

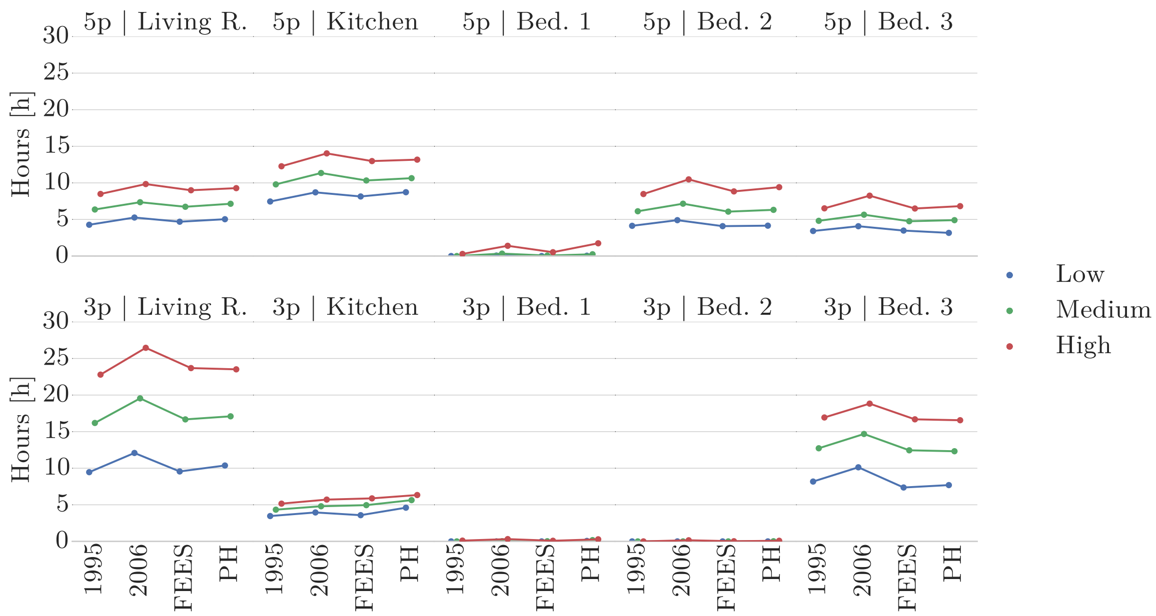


Figure 5.14: London (daytime purge) PPD-weighted average hours: window-to-floor glazing ratio

first and there is always someone during solar peak hours in the second. For the family it is west and east because occupancy is greater there and the shading ineffective for lower Sun altitudes. The same applies to the kitchen of both occupancy scenarios. Obviously, north is the most favourable orientation when the only aspect that matters is overheating.

This breakdown of parameters has shown some of the difficulties of assessing overheating

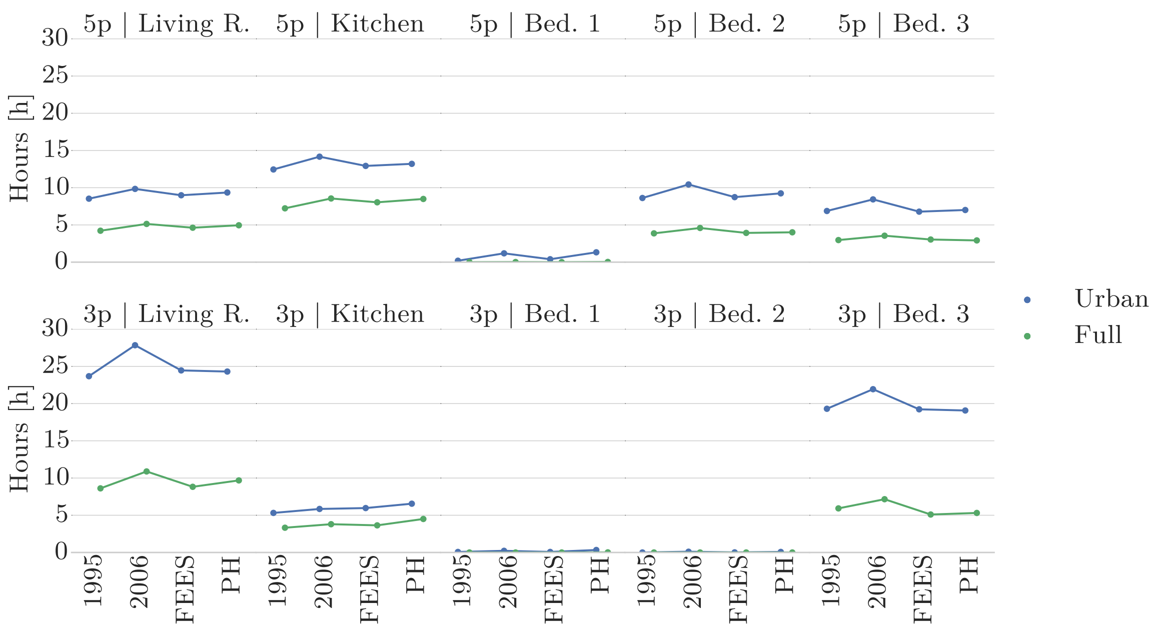


Figure 5.15: London (daytime purge) PPD-weighted average hours: shading

risk given a closed context (i.e. collapsing everything else under the current view). It was known beforehand that PH would perform in general terms better than other construction but this was not be true for every single case of the breakdown. The key strategy to test the hypothesis was to consider a perspective as general as possible through pairwise comparisons to avoid the potentially misleading findings when keeping a close view to a multi-dimensional problem. This could have been approached with a sensitivity analysis, but this way was preferred to keep the discussion closer to changes in performance directly related to the energy transferences, which, in turn, can be contrasted to the findings covered in the literature review.

In this regard, it has been shown that, the moment windows can be opened enough to provide at least the same infiltration rate between constructions, insulation and airtightness are better understood as an efficiency measure. They can only be categorized as a 'cooling strategy' when no other means are possible. Whether insulation or airtightness is the most influential parameter is a function of their relative role within their building standards. For the example shown, insulation accounted for 70% of the difference in performance of a 1995 dwelling when compared to a PH. On the contrary, it was only responsible for 10% in the PH. Altogether, these cases justify the contradictions in the performance of better building fabric in the literature review. Each of the statements reviewed has a certain ambit where they hold truth but when appraising holistically the range 1995–2006–FEES–PH for realistic scenarios —where some sort of purge ventilation is an option—, better construction standards not only do not increase the risk, they are also capable of lowering it significantly.

5.4 Overheating criteria

To test the second hypothesis the TM-36, TM-52 and PH criteria were plotted together in the same fashion as previous indicators (fig. 5.17). The results are expressed as the percentage of rooms of the considered slice of the simulations that overheat. If the recommendations of the

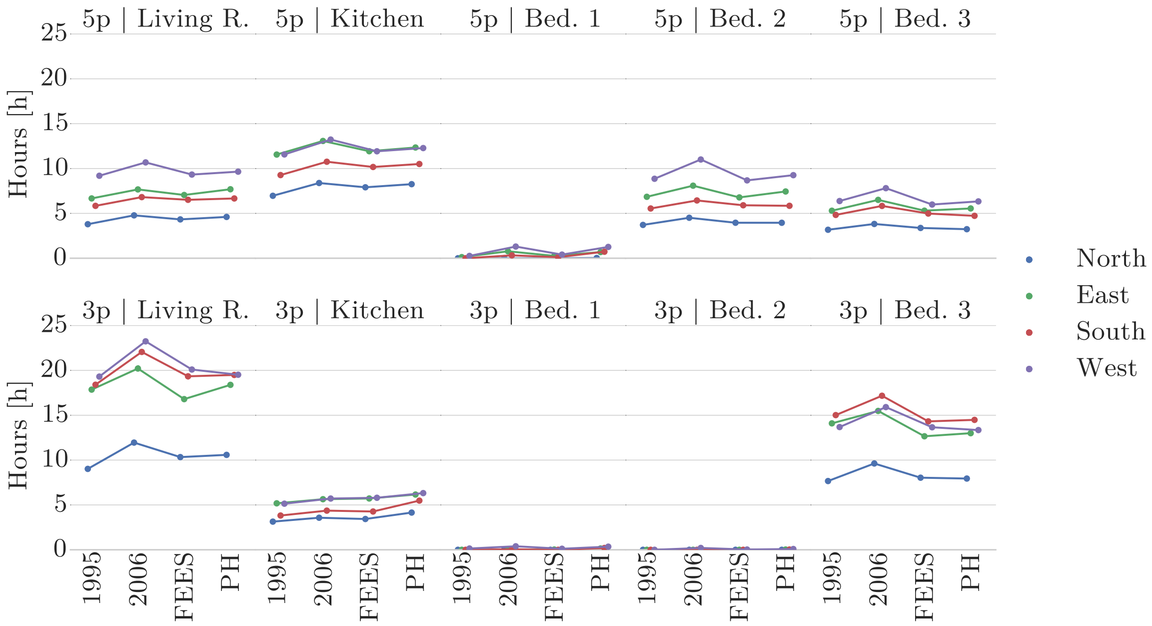


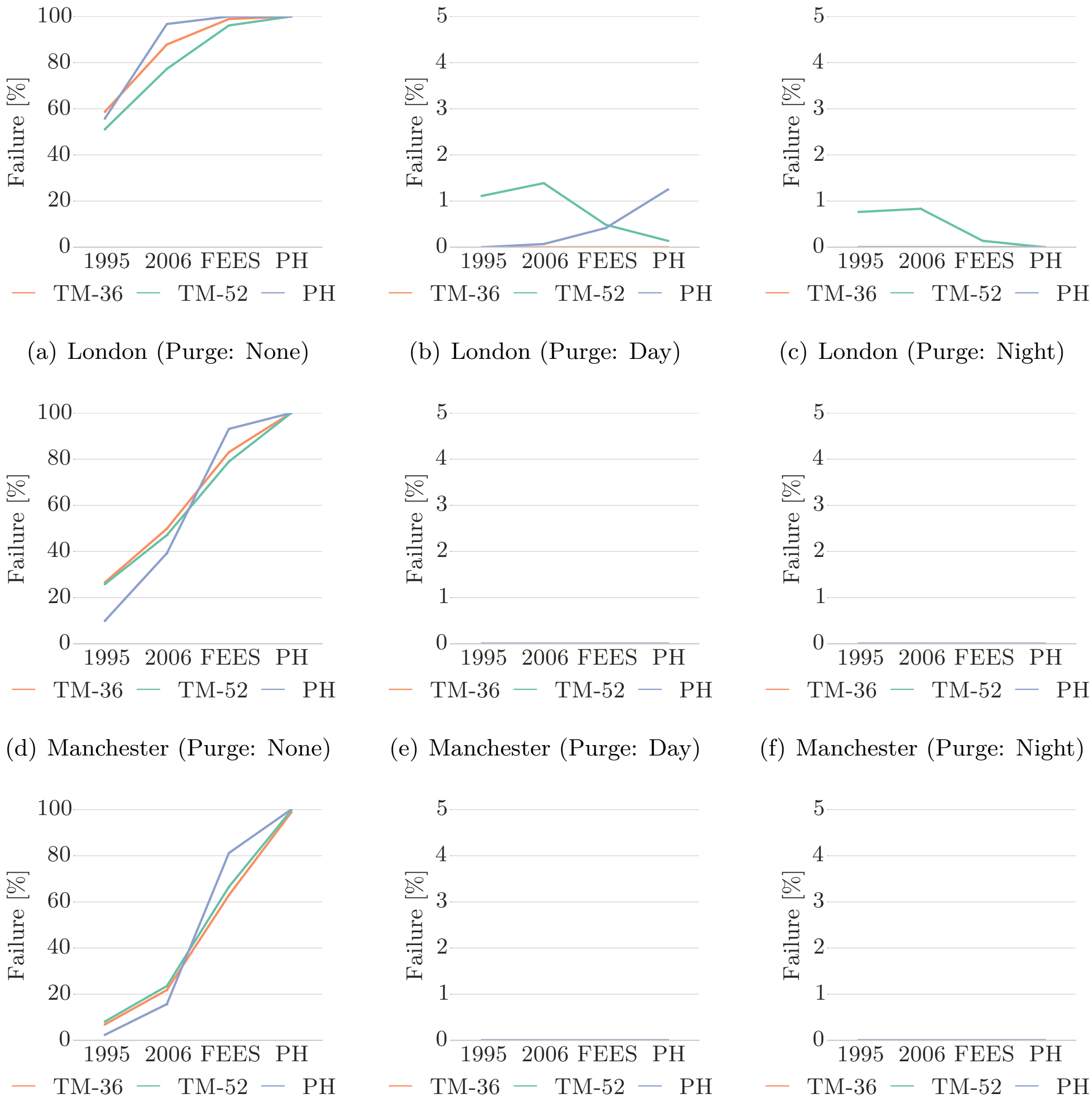
Figure 5.16: London (daytime purge) PPD-weighted average hours: orientation

EN-15251 were to be followed, it could have been considered that the whole house overheats if any of its rooms did since they represent at least 5% of the total floor area (BSI 2007). However, reporting each room achieves a better resolution for the purposes of this paper.

The general performance remains qualitatively the same when compared to the independent characterization of overheating, with a high failure rate in London when purge is not allowed. When windows can be opened, figures drop to the range between 0 to 2% in London, being irrelevant for Manchester and Edinburgh. To contextualize them it should be reminded that 50% of the rooms of each graph do not have shading or that 33% have low thermal mass or high glazing ratio. Thus, the values obtained are considered reasonable since the external temperature is generally colder than the comfort range.

The main outcome is that different overheating criteria *can* result in different *trends*, proving the second hypothesis. When purge ventilation is allowed for London, each of the three standards identifies different trends for daytime purge: the risk of TM-52 decreases after the local increase in 2006, PH increases and TM-36 does not capture overheating. Obviously, the trend of TM-52 is coherent with those identified in the previous section since they are both based on the same ACM. If it is considered that this thermal comfort model is more appropriate for overheating in free-running buildings, this leads to question the results obtained with the fixed thresholds of TM-36 and PH. The discrepancy it is not surprising taking into account previous conclusions regarding pass/fail limits.

It can also be noted that the risk identified by the TM-52 is greater than that of TM-36. This is due to choosing TRY weather files since its running mean results in maximum comfort temperatures below the 28 °C of the TM-36 (e.g. fig. 4.4). When the risk of overheating is high in absolute terms —no purge—, TM-52 identifies slightly lower failure because it is based on three criterions of which at least two have to be met. That TM-36 scores higher means that severity is the driver or the risk, fact already known through the decomposition of hours in different ΔT_o (fig. 5.9). For the cases where purge ventilation is allowed, the ranking



(a) London (Purge: None) (b) London (Purge: Day) (c) London (Purge: Night)

(d) Manchester (Purge: None) (e) Manchester (Purge: Day) (f) Manchester (Purge: Night)

(g) Edinburgh (Purge: None) (h) Edinburgh (Purge: Day) (i) Edinburgh (Purge: Night)

Figure 5.17: Overheating criteria (indicator 2): Percentage of rooms that fails the criteria (Note: Y axis scale adapted for *Purge: None*)

correspond with the magnitude of ΔT. Here, the risk of overheating is driven by duration in such situations, triggered first in the TM-52 because of the relatively cold running mean and its relationship with the behaviour modelled to open windows. Lastly, these results suggest that the criteria are useful to communicate the risk of overheating but research should not rely on them exclusively to appraise how it changes between different scenarios.

5.5 Energy demand

The discussion regarding insulation and overheating has its roots in the idea that improvements of heating energy demand affect the cooling one. Figure 5.18 shows the results of the heating demand grouped by standard and location, where the energy demand is apparently low for 1995 and 2006. The reference for them is energy *consumption* which takes into account Domestic Hot Water (DHW) and the efficiency of the equipment. Considering that DHW is about 30% and a boiler efficiency of 85%, values would be 1.5 times greater, in the range of known consumptions (Palmer and Cooper 2013; BRE 2005). On the contrary, FEES and PH specify their heating energy demand, being the average of the locations close to the goals of 39 and 15 kWh/m^2/year, respectively. FEES and PH achieve their goals by an iterative design process, meaning that the dispersion in the demand is a consequence of the propagation of cases that have not been optimized to satisfy them.

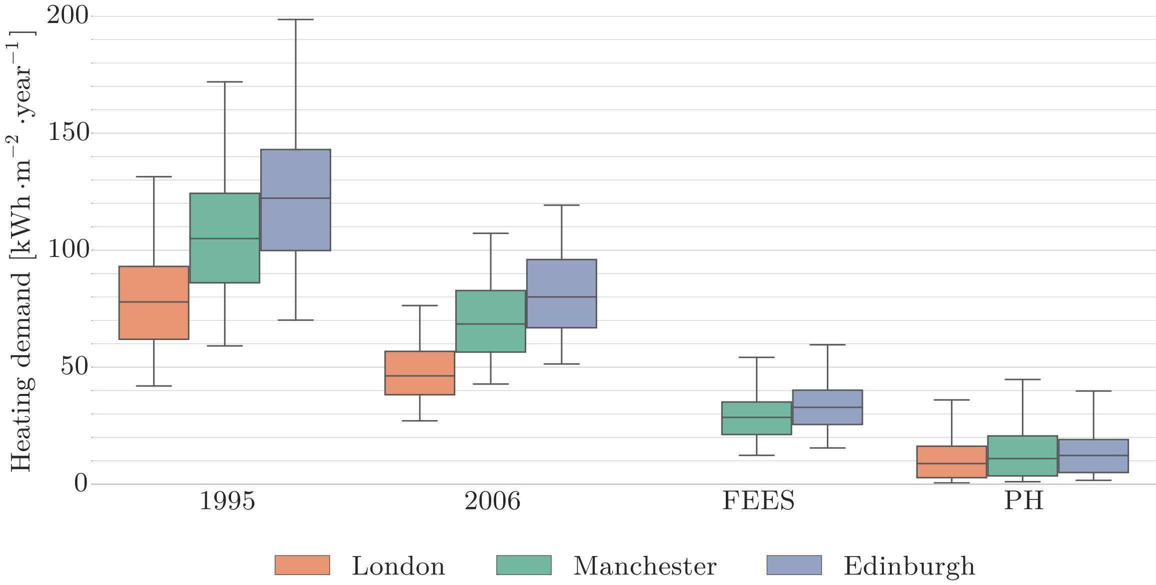
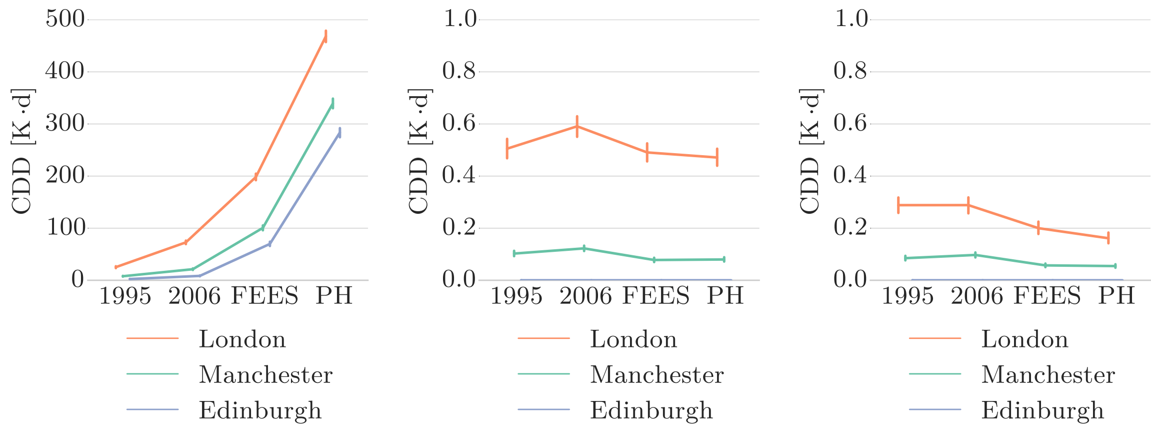


Figure 5.18: Heating energy demand intensity

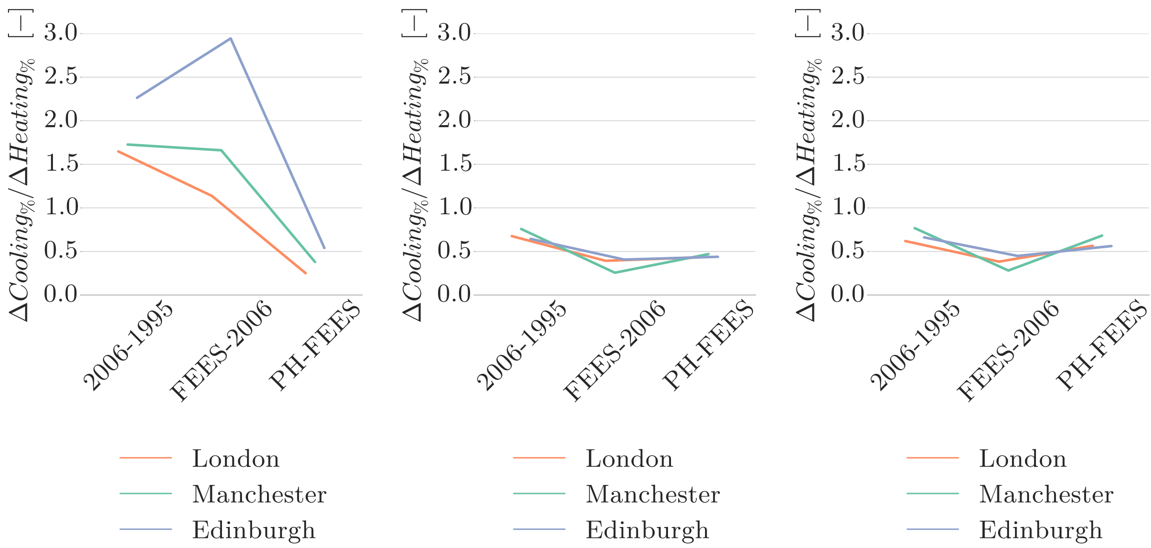


(a) Purge: None

(b) Purge: Day

(c) Purge: Night

Figure 5.19: Cooling energy demand (indicator 3): CDH for 25 °C when above ACM $T_{cm,max}$ (Note: Y axis scale adapted for *Purge: None*, CI:95%)



(a) Purge: None (b) Purge: Day (c) Purge: Night

Figure 5.20: Relative increments of cooling and heating energy demand

Figure 5.19[6] shows an approximation to the CDD obtained considering that if the building overheats and surpasses the PMV-PPD upper limit it would be cooled down to 25 °C. It has to be stressed that this is an approach since it does not take into account latent heat nor the new energy balance that this internal temperature would entail nor the HR in PH. The trend is the same as the one seen before but with the benefits of FEES and PH more obvious as cooling would only be required for the higher peaks. In fact, greater differences could be expected when solving the limitations of this approach as greater insulation, airtightness and HR would yield lower demands.

Due to the difficulties of translating CDD to consumption (CIBSE 2006), fig. 5.20 quantifies the changes by comparing relative increments of cooling and heating energy demand. A value of one means that the change in heating translates to the same relative change in cooling, less that savings in heating are higher than the potential increases in cooling and greater one the opposite. This is a conservative estimate since the heating demand is much larger than the cooling one in the UK. Despite this, it is seen how in the majority of cases the idea that changes in heating directly translate into cooling is not valid. Even PH reports net savings when purge is forbidden, whereas other constructions can still be expected to report absolute savings since changes of 1% in heating can be considered greater than the maximum of 3% obtained for FEES–2006 in Edinburgh.

5.6 Summary

This chapter has appraised the fundamental aspects of overheating in mid-terraces built to meet four different standards, namely 1995, 2006, FEES and PH. The independent characterization was based in the description of different properties of discomfort showing two possibilities. If purge ventilation is not allowed 1995 performs significantly better due to its air leakage and

[6] Complete description in appendix C.

lower insulation levels. This is possible since in the UK external temperatures are generally colder than the maximum comfort one. Nevertheless, this scenario was modelled as an extreme situation unlikely to be found in reality as the risk is considerably greater than when purge ventilation is available. If windows can be opened, better performance is progressively achieved by FEES and PH. For low but frequent overheating with daytime purge 1995 yields lower duration of overheating but for severer periods or nighttime purge FEES and PH greatly outperforms it. For the cases where windows can be opened, this translates in lower maximum temperatures, overall discomfort and failure rate when appraised through standard criteria. In addition, it was shown that standard overheating criteria can result in the identification of different trends in the risk. Finally, it has been demonstrated that savings in the heating demand do not translate into equivalent increases of the cooling one. In this aspect, better building fabric achieves not only great reductions in heating but also in cooling since it is required when overheating is severe.

CHAPTER 6

Analysis and discussion: future weather

The previous chapter has shown how better building fabric is significantly more beneficial to lower overheating risk in realistic scenarios than the others. In fact, they could outperform them in every situation if the differences in airtightness could be satisfied by, for instance, increasing the ventilation rate or through small openings. 1995 was able to take advantage from its air leakage and lower insulation when windows were shut or the overheating risk not severe because the external environment is colder than the neutrality temperature, which is the prevailing situation currently in the UK. This was translated as the same or lower risk when overheating took place in ΔT between cero and one. CIBSE (2005) partly hinted this situation but subsequent research has tended to focus in similar standards, where this effect is greatly diminished. The insights of section 5.3.4 has shown how airtightness can be considered irrelevant once a specific framework with some sort of purge ventilation is set up.

Therefore, it is of interest to corroborate and expand previous findings under a warmer weather. One of the options would be to simulate the dwelling in hotter climates but this task is very difficult in practical terms. Dwelling typologies change between countries, as well as typical constructions, occupancies and behaviour. To keep the research relevant to real cases and to address the concerns of resilience, previous models were also simulated using the current UK climate change projections of UKCP09 (Centre for Energy and the Environment 2011). Hence, the London 2080 for the high emissions scenario with 90% probability (TRY) was chosen to clarify the performance in this extent (fig. 6.1). Manchester and Edinburgh were omitted for brevity, as their risk would fall between these cases. Regarding adaptive comfort, it can be seen the new relationship between external temperatures and comfort thresholds, being expected more frequent and severer overheating (fig. 6.2). Nevertheless, the monthly temperatures still depict averages predominantly below neutrality.

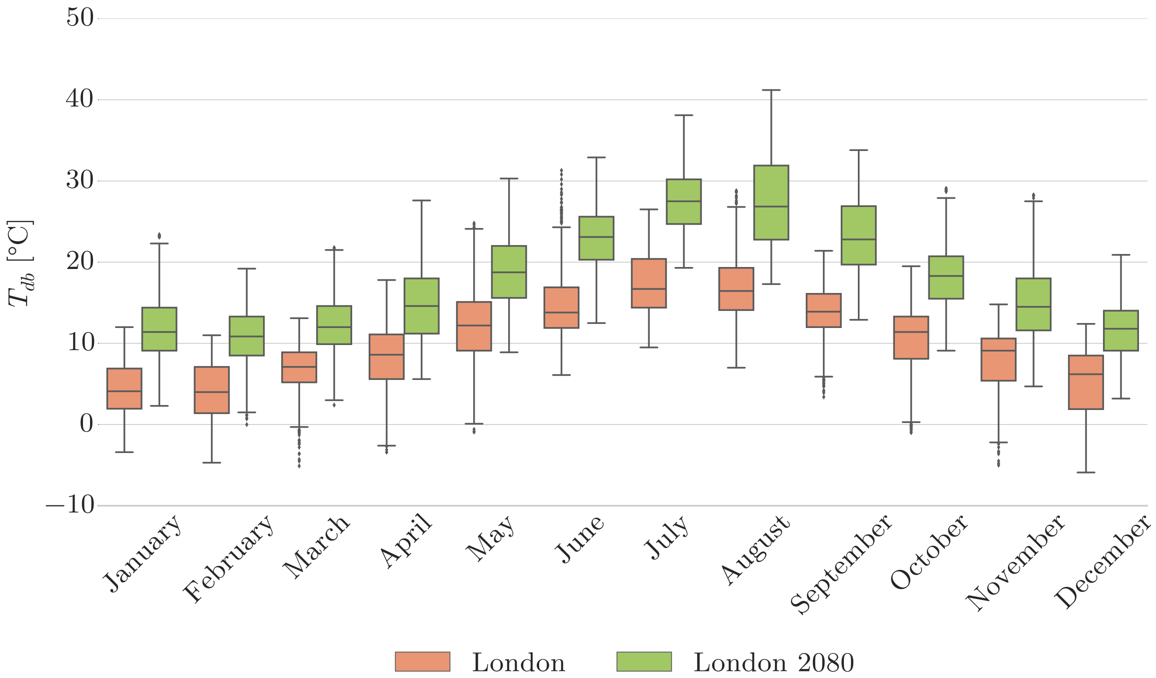


Figure 6.1: Dry bulb temperature summary for the locations

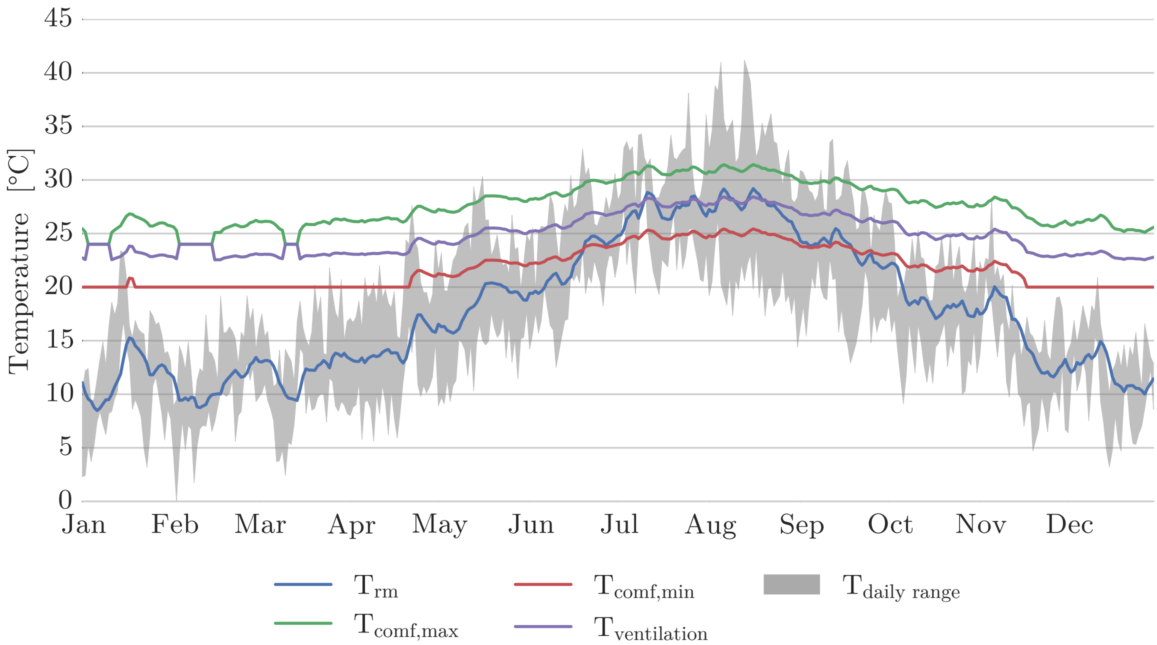
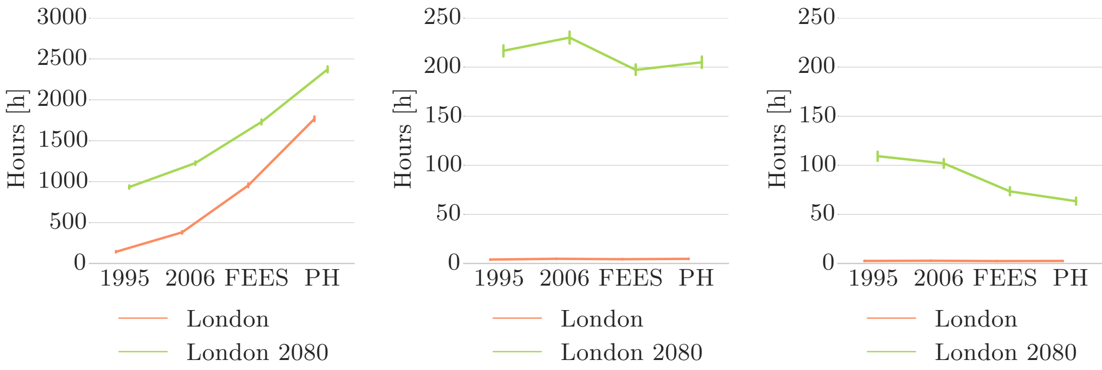


Figure 6.2: London 2080 (TRY, High emissions, 90% probability) purge ventilation temperature trigger: Day

6.1 Independent characterization

6.1.1 Duration

The results for London 2080 clearly show the performance and drivers of building fabric identified in the previous chapter (fig. 6.3[1]). Yet, the most notorious change is the new absolute values for the risk. When windows are shut there is a general increment, but not as steep as in the cases where they can be opened. Under current TRY, daytime purge means were on the range 4–5 h, whereas here they are 190–240 h. This illustrates that ventilation is not as effective, given that external temperatures now surpass the upper threshold more often. Nonetheless, purge remains essential when compared to the case where windows cannot be opened. This further supports the idea that new buildings have to be aware of potential future conditions to minimize the effects of overheating from the design stage since it affects glazing ratios and the strategies for natural ventilation and shading.



(a) Purge: None (b) Purge: Day (c) Purge: Night

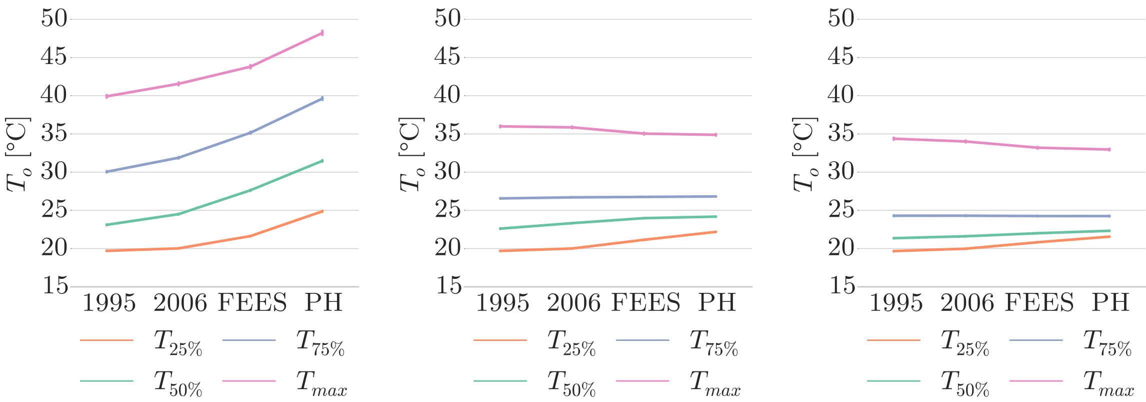
Figure 6.3: Duration (indicator 1-1): London average hours above ACM $T_{cm,max}$ (Notes: London 2080 —High emissions 90% probability— and Y axis scale adapted for *Purge: None*, CI:95%)

The ranking of building fabric when purge ventilation is not allowed remains unaltered because the annual average temperature is still below neutrality. However, the relative increments of each standard greatly vary. The duration of the PH —the worst case— is now 1.3 times higher than before whereas in 1995 it is 6.6 greater. This is due to the fact that airtightness is not as beneficial in 2080 as it was before given the temperature rise already mentioned. The other cases show clear improvements for FEES and PH. Daytime purge was not favourable in this metric previously because a significant part of overheating was for increases up to 1 K. Now they show improvements of 9 and 5%, respectively. More substantial are the differences when windows can be opened during the night, where FEES overheats 33% less than 1995 and PH 42%. Even 2006 reports lower overheating despite its relationship between airtightness and insulation.

[1]The new results are contextualized with the previous ones for London whenever possible. In the case of the breakdown in section 6.1.2 they will be omitted as they would have been the reproduction of the same subplots as in section 5.3.2. The tables and distribution of the new cases are shown in appendix C since they follow equivalent patterns as before.

6.1.2 Severity

The overall rise in risk also translates in evident benefits in severity for improved building fabric when purge is available (fig. 6.4). The behaviour is now clearly optimal: the lower temperatures during wintertime are kept above comfort —20 °C—, reducing the heating demand, whereas in the summer they are lowered, keeping the house cooler. On the contrary, the range for 1995 is wider, with minimums lower than 20 in winter and maximums beyond 34 °C (winter and summer, respectively). The new scenario is equivalent to that of the previous indicator when windows cannot be opened: greater insulation and airtightness yields higher temperatures. Yet, the relative performance is worse for the lower ones when compared to the previous results. It has to be stressed that this is a *theoretical* case to contrast and quantify findings as the maximum temperatures are beyond the known health risk threshold.



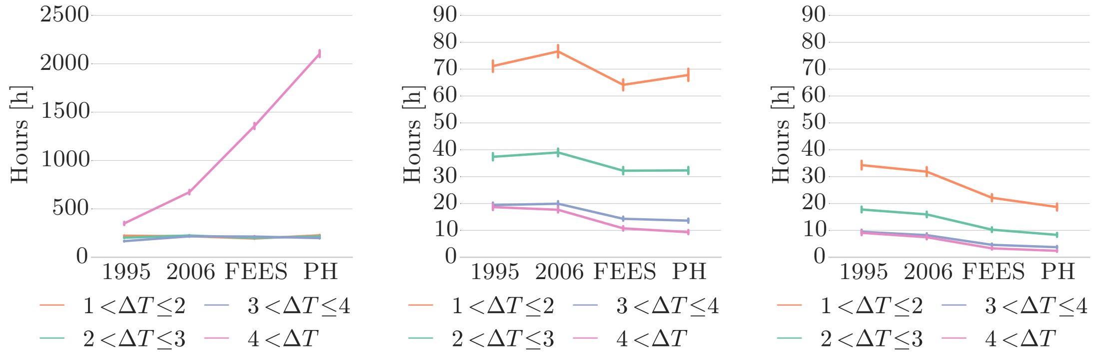
(a) London (Purge: None) (b) London (Purge: Day) (c) London (Purge: Night)

Figure 6.4: Severity (indicator 1-2): London 2080 (High emissions, 90% probability) average internal temperature (CI:95%)

Figure 6.5 provides better insights of what is happening when temperatures are beyond $T_{cm,max}$. Except for when purge is not allowed, improvements to the building fabric translate in increasing advantages as severity grows. The initial bins when windows can be opened during daytime show the same dispersion of previous results and the same benefits for extremes, which are further lowered when they can be opened all day long. Despite the overall warmer temperatures, the daily swing still provides temperatures colder than neutrality during the night: there is the opportunity to lower the risk by about half for the following day if occupants were to operate them correctly.

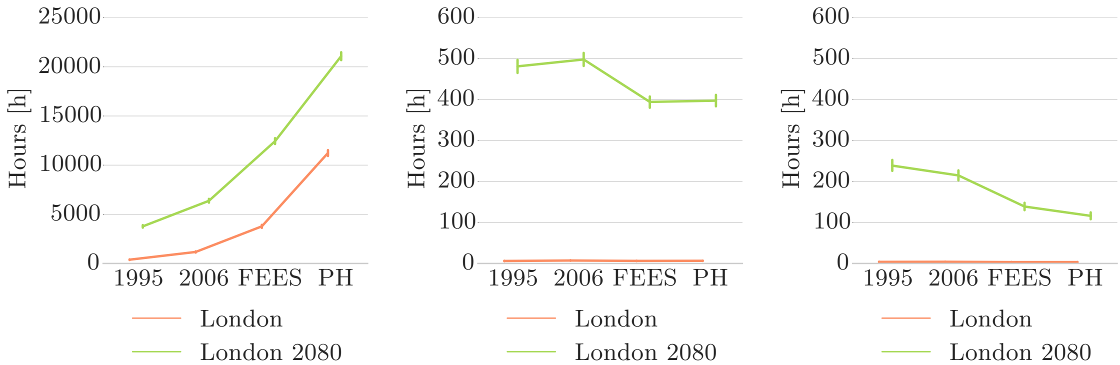
6.1.3 Discomfort

The weighting according to the PPD expands on the results of duration, making clearer that, under this climate projection, the risk increases significantly more when windows can be operated than when they cannot (fig. 6.6). Under current TRY, the means ranged 300–12 000 h for purge ventilation not available, 6–7 h for day and 3–4 h for night, whereas here they are 3700–21 100 h, 390–480 h and 110–240 h, respectively. Discomfort follows the previous trends, registering greater satisfaction for FEES and PH in both the average and the peaks (fig. 6.7).



(a) London (Purge: None) (b) London (Purge: Day) (c) London (Purge: Night)

Figure 6.5: Severity (indicator 1-2): London 2080 (High emissions, 90% probability) average hours breakdown for ΔT above ACM $T_{cm,max}$ (Note: Y axis scales adapted for *Purge: None*, CI:95%)



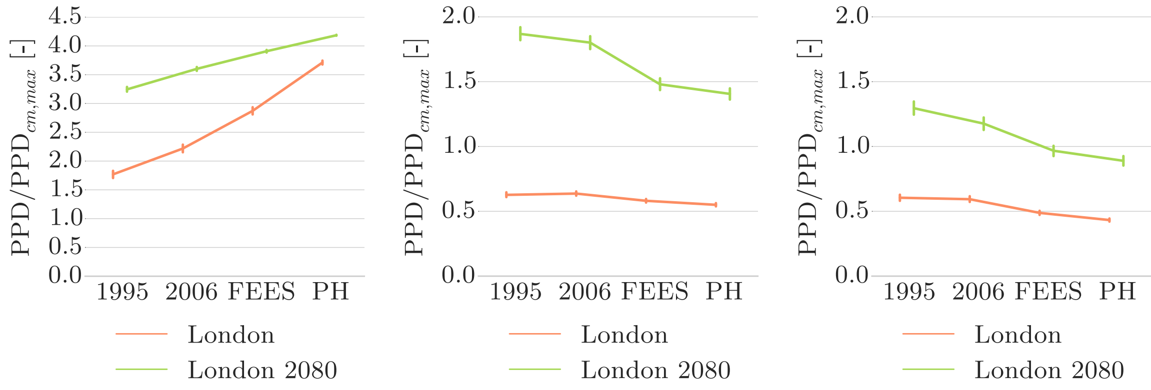
(a) Purge: None (b) Purge: Day (c) Purge: Night

Figure 6.6: Discomfort (indicator 1-3): Average PPD-weighted hours above ACM $T_{cm,max}$ (Notes: London 2080 —High emissions 90% probability— and Y axis scale adapted for *Purge: None*, CI:95%)

6.2 Overheating criteria

The application of TM-36, TM-52 and PH criteria for London 2080 further reinforces the second hypothesis (fig. 6.8). Everyone result in a 100% of failure when appraising the case where purge is not available but the situation differs for the others. The average of TM-52 in the middle one is between 70 and 80%, with higher and lower trends depending on the case. Here, TM-36 and PH keeps reporting that every room does not meet their criteria. The discrepancy is greater when purge ventilation is available all day long, with TM-52 depicting less risk as the fabric is improved, PH a marginal advantage and TM-36 still achieving general failure.

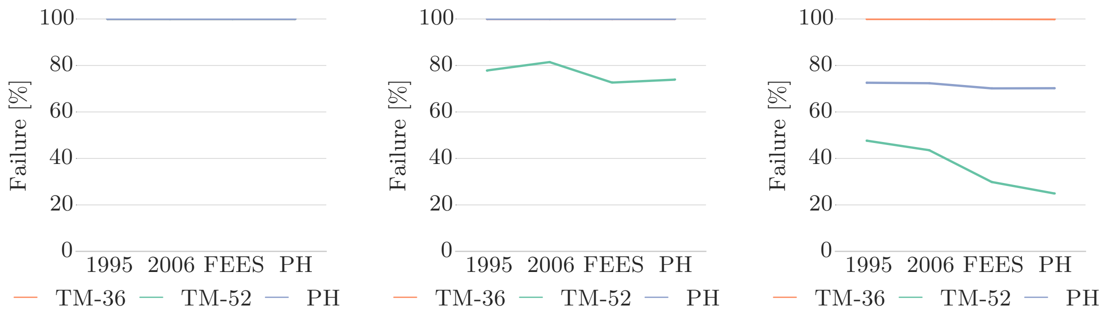
Unlike the results for the current TRY, the TM-52 reports lower risk than TM-36 —in the lines of overheating research focused on future climate projections—. This is due to the general rise in temperatures, which surpass the fix threshold of 28 °C more than the limit of



(a) Purge: None (b) Purge: Day (c) Purge: Night

Figure 6.7: Discomfort (indicator 1-3): London PPD over PPD$_{\mathrm{cm,max}}$ (Notes: London 2080 —High emissions 90% probability— and Y axis scale adapted for *Purge: None*, CI:95%)

1% of the time (fig. 6.2). Simultaneously, ACMs consider that people would adapt to the new temperature profile, reflected in the new running mean, higher than the previous and thus lowering substantially the failure rate. Interestingly, PH failure is lower than TM-36 as well: this benchmark does not penalize severity as much as it is in the latter and allows for more time of discomfort at a lower threshold (25 °C for 10% of the time).



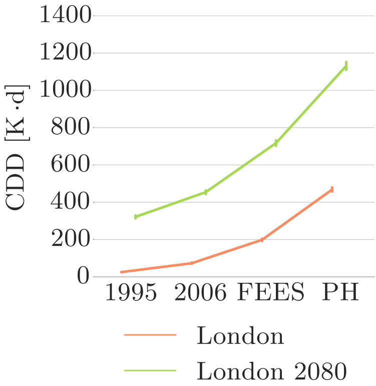
(a) London (Purge: None) (b) London (Purge: Day) (c) London (Purge: Night)

Figure 6.8: Overheating criteria (indicator 2): London 2080 (High emissions, 90% probability) percentage of rooms that fails the criteria (Note: Y axis scale adapted for *Purge: None*)

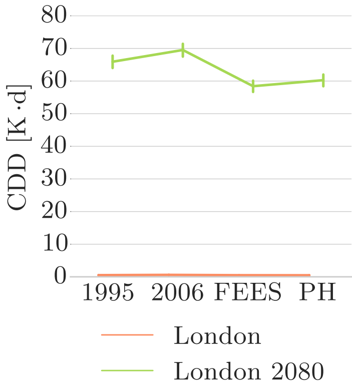
6.3 Energy demand

The appraisal of future energy demand requires careful considerations of the methods and climate projections to be used. Although it is possible to apply the same approach as before, results do not have to be necessarily representative nor adequate given that the high emissions scenario with 90% has been selected to capture a higher overheating risk. In addition, it could be argued for the current TRY that the energy demand does not feature a significant cooling share when compared to that of that of heating, whereas research in this topic has shown that this might not be the case under climate change. The studies reviewed in chapter 2 coincide that the demand in the UK will still be driven by heating but they differ in the relative contribution of cooling (e.g. Collins et al. (2010) and Gupta et al. (2015)). Because of this only the approximation of CDD will be discussed.

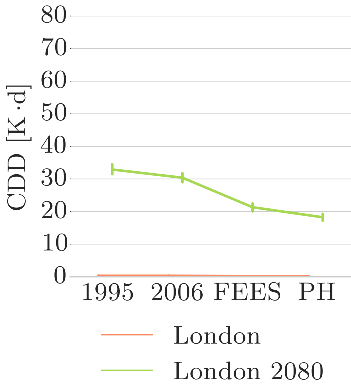
Figure 6.9 shows the same trends as for the current weather. The ranking of building standards is maintained, with 1995 featuring a higher relative increment to the previous scenario as with the indicators already discussed. The consideration of a projection with higher temperatures emphasises the benefits derived of greater insulation and airtightness for cooling. In the case of daytime purge, FEES and PH have a demand 12% lower than that of 1995 and 2006, improving to 36% if windows could be opened during the night as well due to contribution of thermal mass.



(a) Purge: None



(b) Purge: Day



(c) Purge: Night

Figure 6.9: Cooling energy demand (indicator 3): London 2080 (High emissions, 90% probability) CDH for 25 °C when above ACM $T_{cm,max}$ (Note: Y axis scale adapted for *Purge: None*, CI:95%)

6.4 Summary

The consideration of the climate change projection for London in 2080 (TRY, high emissions scenario and 90% probability) has corroborated and expanded the findings of the previous chapter. This has allowed the appraisal of warmer temperatures while keeping the models relevant, showing that the options of FEES and PH are resilient. 1995 is still the case that reports lower overheating risk when purge ventilation is not allowed because the average external temperature remains below the upper comfort limit, although its benefits have been hindered following the warmer weather. Nevertheless, unlike previous results, FEES and PH standards achieve significantly lower overheating and cooling demand in *every* other case. This further reinforces that the occasional better performance in the real scenarios of 1995 for current TRY is due solely to the advantageous external temperatures and milder risk. Overall, these findings supports those studies that associated higher insulation levels and airtightness with lower overheating, having been explained and bounded the situations and causes of results in other lines.

CHAPTER 7

Conclusions

The role of building fabric in overheating risk, and insulation in particular, has been subject of numerous studies in the last decade that have arrived at apparently contradictory conclusions regarding its performance. This paper has looked at four fabric standards that have been considered representative of the situations the UK building sector has to address, pursuing a holistic appraisal that, building on previous research, could clarify how they relate to overheating. The model was based on a real mid-terrace dwelling built to meet the CSH to Level 4, allowing its validation, which was then adapted to 1995 and 2006 Building Regulations and the voluntary standards of FEES and PH. This way the typical ranges of retrofits and the aspirations for lower energy demand of the voluntary schemes were addressed under the same study. To be congruent with each of these, parametric building simulations were carried out according to their contexts and covering the variables and cases widely recognized as overheating drivers.

Three hypotheses were established following the identified limitations in the definition of overheating and implied ideas found in the literature reviewed. The first one addressed the role of improved building fabric through an independent characterization of the properties of discomfort —namely duration, severity and dissatisfaction—. Due to the reliance of previous research in different overheating metrics, the second was aimed at testing their congruence in the identification of the same trends between cases. Lastly, changes in the annual energy demand resulting from each standard were approximated to quantify whether improvements in heating translated in increases of cooling or not.

The result regarding the first hypothesis is two-fold. The combination of insulation, airtightness and ventilation for 1995 translates in lower overheating risk for the cases where purge ventilation is not available since the external temperatures are often below the maximum comfort one in the current UK weather. In addition, it outperforms other standards when the risk is driven by mild temperatures under daytime purge, as it was the case of London and Edinburgh. On the contrary, the higher insulation and airtightness delivered in FEES and PH makes them the best option against severer overheating (e.g. Manchester due to greater daily swings) or when windows can be operated during the night. Therefore, they always achieve greater comfort under high risk when any sort of purge ventilation was available. Given the high levels of overheating when windows remain closed, the advantages of 1995 were considered irrelevant for real scenarios. The insights of future performance under London 2080 climate change projections (TRY, high emissions, 90% probability) further reinforced these findings. FEES and PH have proven to be more reliable in diminishing the risk for every indicator when purge ventilation was available. Altogether, the casuistic gathered in previous research arose in the process, being explained when their findings were valid in this project.

For the second objective, it has been demonstrated that different overheating criteria can identify different trends between pairwise comparisons in both the current and future weathers considered. This was due to the built-in algorithms to compute the risk, which are not congruent between them. In addition to the way they were derived, it is concluded that they should not be used as the only metric to appraise performance, at least for research. Of the three benchmarks evaluated, the TM-52 is closer to current ACMs and thus deemed more appropriate.

The third hypothesis concluded that savings in the heating energy demand through the building fabrics assessed do not translate in absolute increases of the cooling one. Yet, they can raise it in relative terms for the extreme case where purge is not available. For the considered projection of London 2080, the approximation of the CDD showed the same trends, with substantial savings in demand in FEES and PH if windows can be operated.

Overall, the results of this study indicate that the goals of lowering carbon emissions, providing resilient dwellings and delivering greater comfort can align through improved building fabric. Besides the evidence gathered, further efforts are deemed necessary to ensure these are applicable outside the scope established here.

7.1 Recommendations for future work

1. Further investigation on the limits of discomfort due to overheating. The lack of a definition and the quantification of what is acceptable impede the appraisal and optimization of solutions. Regarding research, the development of criteria that do not rely on pass/fail thresholds would be of interest since they make the analysis more complex and do not relate to real perception of comfort.

2. One of the major concerns regarding overheating is the increase in morbidity and mortality it can entail, specially taking into consideration current climate change projections. It is then essential to research how indoor temperatures correlate to them to allow studies on countermeasures.

3. Additional investigation on natural ventilation models and the influence of the Urban Heat Island in them are mandatory to provide reliable predictions of performance given the role purge ventilation plays in overheating.

4. Due to the limitations of this project, only a mid-terrace was considered. The methods presented here should be further developed (e.g. implementation of mix-mode strategies) and applied to other dwellings —especially flats, since they are known to be at a high risk as well—.

5. The ranking of building fabrics was sensitive to the external weather as its average temperature and daily swings can promote or hinder certain features. Further research should consider a wider spectre of locations and climate change projections to map and assess major trends.

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APPENDIX A

Conditions of the data

Following there are the conditions under which data of the case study was made available. Therefore, information regarding the case study was kept anonymous. Unless otherwise indicated, facts and data regarding them correspond to the authors and personal responsible for the project. To ensure academic rigour, a copy of these documents was made available to the supervisor of this dissertation.

> "The data is used anonymously without any reference to individual properties, dwellings or users so that there is no recourse to ###### in terms of data protection issues.
>
> There is no exclusive right for the data to be used by yourselves or the university and that we are free to use the data for our own purposes or to share with other organisations, or universities for their own research projects going forward.
>
> We can have access to the research that you are doing using our data where that can help us inform our own strategy for delivering sustainable homes going forward."

APPENDIX B

Extended input

B.1 Materials

Table B.1: Materials 1/2: non-insulating materials (Data source: CIBSE (2015) and LBNL (2015))

Material	d [m]	λ [W m^{-1} K^{-1}]	ρ [kg/m^3]	c_p [J kg^{-1} K^{-1}]	Thermal absorptance [−]	Solar absorptance [−]	Visible absorptance [−]
Brick	0.1	0.77	1750	1000	0.6	0.9	0.9
Brick	0.05	0.77	1750	1000	0.6	0.9	0.9
Brick slips	0.02	0.56	1750	1000	0.9	0.5	0.5
Carpet	0.005	0.6	200	1300	0.9	0.7	0.7
Concrete block	0.05	0.77	700	1000	0.94	0.6	0.6
Concrete hollowcore slab	0.2	1.13	900	1000	0.9	0.7	0.7
Concrete slab	0.2	1.33	2000	1000	0.9	0.7	0.7
Mineral Wool	0.05	0.04	12	1450	0.9	0.7	0.7
Plaster	0.015	0.57	1300	1000	0.91	0.4	0.4
Plaster	0.02	0.57	1300	1000	0.91	0.4	0.4
Plasterboard	0.01	0.21	700	1000	0.91	0.4	0.4
Plasterboard (dense) x2	0.03	0.21	900	1000	0.91	0.4	0.4
Plywood	0.015	0.57	1300	1600	0.9	0.7	0.7
Screed	0.02	0.46	1200	1000	0.9	0.7	0.7
Tiles	0.025	1.8	2000	1400	0.9	0.65	0.65
Timber flooring	0.01	0.13	500	1600	0.9	0.7	0.7
Timber structure	0.2	1	80	1000	0.9	0.7	0.7

Table B.2: Materials 2/2: insulating materials (Data source: CIBSE (2015) and LBNL (2015))

Material*	d [m]	λ [W m^{-1} K^{-1}]	ρ [kg/m^3]	c_p [J kg^{-1} K^{-1}]	Thermal absorptance [−]	Solar absorptance [−]	Visible absorptance [−]
I:G:1995:H	0.076	0.04	15	1450	0.9	0.7	0.7
I:G:1995:L	0.074	0.04	15	1450	0.9	0.7	0.7
I:G:1995:M	0.073	0.04	15	1450	0.9	0.7	0.7
I:G:2006:H	0.147	0.04	15	1450	0.9	0.7	0.7
I:G:2006:L	0.145	0.04	15	1450	0.9	0.7	0.7
I:G:2006:M	0.144	0.04	15	1450	0.9	0.7	0.7
I:G:FEES:H	0.209	0.04	15	1450	0.9	0.7	0.7
I:G:FEES:L	0.207	0.04	15	1450	0.9	0.7	0.7
I:G:FEES:M	0.206	0.04	15	1450	0.9	0.7	0.7
I:G:PH:H	0.387	0.04	15	1450	0.9	0.7	0.7
I:G:PH:L	0.385	0.04	15	1450	0.9	0.7	0.7
I:G:PH:M	0.384	0.04	15	1450	0.9	0.7	0.7
I:R:1995:H	0.147	0.04	15	1450	0.9	0.7	0.7
I:R:1995:L	0.151	0.04	15	1450	0.9	0.7	0.7
I:R:1995:M	0.14	0.04	15	1450	0.9	0.7	0.7
I:R:2006:H	0.147	0.04	15	1450	0.9	0.7	0.7
I:R:2006:L	0.151	0.04	15	1450	0.9	0.7	0.7
I:R:2006:M	0.14	0.04	15	1450	0.9	0.7	0.7
I:R:FEES:H	0.294	0.04	15	1450	0.9	0.7	0.7
I:R:FEES:L	0.299	0.04	15	1450	0.9	0.7	0.7
I:R:FEES:M	0.288	0.04	15	1450	0.9	0.7	0.7
I:R:PH:H	0.387	0.04	15	1450	0.9	0.7	0.7
I:R:PH:L	0.391	0.04	15	1450	0.9	0.7	0.7
I:R:PH:M	0.38	0.04	15	1450	0.9	0.7	0.7
I:W:1995:H	0.074	0.04	15	1450	0.9	0.7	0.7
I:W:1995:L	0.029	0.04	15	1450	0.9	0.7	0.7
I:W:1995:M	0.077	0.04	15	1450	0.9	0.7	0.7
I:W:2006:H	0.1	0.04	15	1450	0.9	0.7	0.7
I:W:2006:L	0.055	0.04	15	1450	0.9	0.7	0.7
I:W:2006:M	0.102	0.04	15	1450	0.9	0.7	0.7
I:W:FEES:H	0.208	0.04	15	1450	0.9	0.7	0.7
I:W:FEES:L	0.163	0.04	15	1450	0.9	0.7	0.7
I:W:FEES:M	0.21	0.04	15	1450	0.9	0.7	0.7
I:W:PH:H	0.386	0.04	15	1450	0.9	0.7	0.7
I:W:PH:L	0.34	0.04	15	1450	0.9	0.7	0.7
I:W:PH:M	0.388	0.04	15	1450	0.9	0.7	0.7

* Key: *L*ow, *M*edium, *H*ighthermal mass.

B.2 Constructions

Table B.3: Constructions 1/4: Ground floor (materials in tables B.1 and B.2)

Construction	Layer name	d [mm]
Ground Floor Lightweight	Carpet	5
	Screed	20
	I:G:*:L	*varies*
	Concrete slab	200
Ground Floor Mediumweight	Carpet	5
	Screed	20
	Concrete hollowcore slab	200
	I:G:*:M	*varies*
Ground Floor Heavyweight	Carpet	5
	Concrete slab	200
	I:G:*:H	*varies*

* According to standard (1995, 2006, FEES, PH).

Table B.4: Constructions 2/4: External wall (materials in tables B.1 and B.2)

Construction	Layer name	d [mm]
External wall Lightweight	Plasterboard	10
	Mineral Wool	50
	I:W:*:L	*varies*
	Brick slips	20
External wall Mediumweight	Plaster	20
	Brick	50
	I:W:*:M	*varies*
	Brick slips	20
External wall Heavyweight	Plaster	15
	Brick	100
	I:W:*:H	*varies*
	Brick slips	20

* According to standard (1995, 2006, FEES, PH).

Table B.5: Constructions 3/4: Roof (materials in tables B.1 and B.2)

Construction	Layer name	d [mm]
Roof Lightweight	Plasterboard	10
	I:R:*:L	*varies*
	Plywood	15
	Tiles	25
Roof Mediumweight	Plasterboard (dense) x2	30
	Timber structure	200
	I:R:*:M	*varies*
	Tiles	25
Roof Heavyweight	Plaster	15
	Concrete slab	200
	I:R:*:H	*varies*
	Tiles	25

* According to standard (1995, 2006, FEES, PH).

Table B.6: Constructions 4/4: Internal floor and partition (materials in table B.1)

Construction	Layer name	d [mm]
Internal Floor Lightweight	Carpet	5
	Timber flooring	10
	Timber structure	200
	Plywood	15
Internal Floor Mediumweight	Carpet	5
	Screed	20
	Concrete hollowcore slab	200
	Plaster	15
Internal Floor Heavyweight	Carpet	5
	Concrete slab	200
	Plaster	15
Internal Partition	Plasterboard	10
	Mineral Wool	50
	Plasterboard	10

B.3 Geometry

Table B.7: Summary of volumes and areas*

Case	TM	Living room		Bedroom 1		Bedroom 2		Bedroom 3		Total	
		V [m^3]	*A* [m^2]	*V* [m^3]	*A* [m^2]	*V* [m^3]	*A* [m^2]	*V* [m^3]	*A* [m^2]	*V* [m^3]	*A* [m^2]
1995	L	65	27	29	12	33	14	56	24	310	133
	M	62	26	28	12	32	14	49	23	289	128
	H	61	26	27	12	31	13	48	23	284	125
2006	L	64	27	29	12	33	14	56	24	306	131
	M	61	26	28	12	31	13	48	23	285	126
	H	60	25	27	11	31	13	48	22	280	123
FEES	L	59	25	27	11	30	13	49	22	279	122
	M	57	24	26	11	29	12	42	22	260	118
	H	56	24	25	11	29	12	41	21	255	114
PH	L	53	22	24	10	27	12	42	20	247	109
	M	51	22	23	10	26	11	36	19	229	104
	H	50	21	23	10	26	11	35	19	222	101

Key: *L*ow, *M*edium, *H*igh. * Volumes and areas of main living spaces, with the total for the whole house.

Table B.8: Frame and dividers geometrical definition according to age and thermal mass

Case	TM	Wall (bare) [cm]	Wall (total) [cm]	Glass [mm]	Recess [cm]	Reveal [cm]	Frame [cm]
1995	L	8.0	10.9	14	5	4.5	5
	M	9.0	16.7			10.3	
	H	13.5	20.9			14.5	
2006	L	8.0	13.5	16	5	6.9	5
	M	9.0	19.2			12.6	
	H	13.5	23.5			16.9	
FEES	L	8.0	24.3	24	5	16.9	10
	M	9.0	30.0			22.6	
	H	13.5	34.3			26.9	
PH	L	8.0	42.0	38	5	33.2	10
	M	9.0	47.8			39.0	
	H	13.5	52.1			43.3	

Key: *L*ow, *M*edium, *H*igh.

B.4 Infiltration

Table B.9: Infiltration: flow coefficient ($m^3\,s^{-1}\,Pa^{-n}$)

Case	Living Room	Kitchen	Toilet	Stairs	Bed. 1	Bed. 2	Bath.	Storage	Bed. 3	Plant room	Shelve	**Total**
1995:H	0.046512	0.016149	0.011652	0.026459	0.011549	0.012885	0.008092	0.005578	0.037833	0.011602	0.004412	0.192724
1995:M	0.031008	0.010766	0.007768	0.017639	0.007700	0.008590	0.005395	0.003719	0.025222	0.007735	0.002941	0.128483
1995:L	0.015504	0.005383	0.003884	0.008820	0.003850	0.004295	0.002697	0.001859	0.012611	0.003867	0.001471	0.064241
2006:H	0.015504	0.005383	0.003884	0.008820	0.003850	0.004295	0.002697	0.001859	0.012611	0.003867	0.001471	0.064241
2006:M	0.010853	0.003768	0.002719	0.006174	0.002695	0.003007	0.001888	0.001302	0.008828	0.002707	0.001029	0.044969
2006:L	0.007752	0.002691	0.001942	0.004410	0.001925	0.002148	0.001349	0.000930	0.006306	0.001934	0.000735	0.032121
FEES:H	0.006202	0.002153	0.001554	0.003528	0.001540	0.001718	0.001079	0.000744	0.005044	0.001547	0.000588	0.025697
FEES:M	0.004651	0.001615	0.001165	0.002646	0.001155	0.001289	0.000809	0.000558	0.003783	0.001160	0.000441	0.019272
FEES:L	0.003101	0.001077	0.000777	0.001764	0.000770	0.000859	0.000539	0.000372	0.002522	0.000773	0.000294	0.012848
PH:H	0.000679	0.000236	0.000170	0.000386	0.000169	0.000188	0.000118	0.000081	0.000552	0.000169	0.000064	0.002812
PH:M	0.000509	0.000177	0.000128	0.000290	0.000126	0.000141	0.000089	0.000061	0.000414	0.000127	0.000048	0.002109
PH:L	0.000339	0.000118	0.000085	0.000193	0.000084	0.000094	0.000059	0.000041	0.000276	0.000085	0.000032	0.001406

Key: *L*ow, *M*edium, *H*igh.

B.5 Schedules and internal gains

Table B.10: Hourly occupancy and electric loads: profile 1 (5 persons)*

	Living Room		Kitchen		Bedroom 1		Bedroom 2		Bedroom 3		Plant room		Total
Hour	O [p]	E [W]	O [p]	E [W]	O [p]	E [W]	O [p]	E [W]	O [p]	E [W]	O [p]	E [W]	O [p]
01:00	0	9.5	0	41.7	2	5.0	1	5.5	2	8.6	0	0	5
02:00	0	9.5	0	41.7	2	5.0	1	5.5	2	8.6	0	0	5
03:00	0	9.5	0	41.7	2	5.0	1	5.5	2	8.6	0	0	5
04:00	0	9.5	0	41.7	2	5.0	1	5.5	2	8.6	0	0	5
05:00	0	9.5	0	41.7	2	5.0	1	5.5	2	8.6	0	0	5
06:00	0	9.5	0	41.7	2	5.0	1	5.5	2	8.6	0	0	5
07:00	1	9.5	1	41.7	1	5.0	1	5.5	1	8.6	0	0	5
08:00	0	9.5	5	41.7	0	5.0	0	5.5	0	8.6	0	0	5
09:00	0	9.5	0	41.7	0	5.0	0	5.5	0	8.6	0	0	0
10:00	0	9.5	0	41.7	0	5.0	0	5.5	0	8.6	0	0	0
11:00	0	9.5	0	41.7	0	5.0	0	5.5	0	8.6	0	0	0
12:00	0	9.5	0	41.7	0	5.0	0	5.5	0	8.6	0	0	0
13:00	0	9.5	0	41.7	0	5.0	0	5.5	0	8.6	0	0	0
14:00	0	9.5	0	41.7	0	5.0	0	5.5	0	8.6	0	0	0
15:00	0	9.5	0	41.7	0	5.0	0	5.5	0	8.6	0	0	0
16:00	0	9.5	0	41.7	0	5.0	0	5.5	0	8.6	0	0	0
17:00	2	9.5	1	41.7	0	5.0	1	85.5	1	88.6	0	1200	5
18:00	2	9.5	1	1291.7	0	5.0	1	85.5	1	88.6	0	1750	5
19:00	2	9.5	1	1291.7	0	5.0	1	5.5	1	8.6	0	1750	5
20:00	2	9.5	1	41.7	0	5.0	1	5.5	1	8.6	0	0	5
21:00	5	150.9	0	1021.1	0	5.0	0	5.5	0	8.6	0	0	5
22:00	5	150.9	0	41.7	0	5.0	0	5.5	0	8.6	0	0	5
23:00	0	9.5	0	41.7	2	5.0	1	5.5	2	8.6	0	0	5
24:00	0	9.5	0	41.7	2	5.0	1	5.5	2	8.6	0	0	5

Key: *O*cuppancy, *E*quimpent * Profile for everyday except for the Plant room (no loads during weekends).

Table B.11: Hourly occupancy and electric loads: profile 2 (3 persons)*

	Living Room		Kitchen		Bedroom 1		Bedroom 2		Bedroom 3		Plant room		Total
Hour	O [p]	E [W]	O [p]	E [W]	O [p]	E [W]	O [p]	E [W]	O [p]	E [W]	O [p]	E [W]	O [p]
01:00	0	5.7	0	41.7	2	3.0	1	3.3	0	5.1	0	0	3
02:00	0	5.7	0	41.7	2	3.0	1	3.3	0	5.1	0	0	3
03:00	0	5.7	0	41.7	2	3.0	1	3.3	0	5.1	0	0	3
04:00	0	5.7	0	41.7	2	3.0	1	3.3	0	5.1	0	0	3
05:00	0	5.7	0	41.7	2	3.0	1	3.3	0	5.1	0	0	3
06:00	0	5.7	0	41.7	2	3.0	1	3.3	0	5.1	0	0	3
07:00	0	5.7	1	41.7	1	3.0	1	3.3	0	5.1	0	0	3
08:00	0	5.7	3	41.7	0	3.0	0	3.3	0	5.1	0	0	3
09:00	2	5.7	0	41.7	0	3.0	0	3.3	1	135.1	0	700	3
10:00	2	5.7	0	41.7	0	3.0	0	3.3	1	135.1	0	1050	3
11:00	1	5.7	1	791.7	0	3.0	0	3.3	1	135.1	0	1050	3
12:00	3	5.7	0	41.7	0	3.0	0	3.3	0	135.1	0	0	3
13:00	2	105.7	0	41.7	0	3.0	0	3.3	1	135.1	0	0	3
14:00	2	105.7	0	41.7	0	3.0	0	3.3	1	135.1	0	0	3
15:00	2	105.7	0	41.7	0	3.0	0	3.3	1	135.1	0	0	3
16:00	2	105.7	0	41.7	0	3.0	0	3.3	1	135.1	0	0	3
17:00	2	105.7	0	41.7	0	3.0	0	3.3	1	135.1	0	0	3
18:00	2	105.7	1	791.7	0	3.0	0	3.3	0	5.1	0	0	3
19:00	2	105.7	1	41.7	0	3.0	0	3.3	0	5.1	0	0	3
20:00	2	105.7	1	863.5	0	3.0	0	3.3	0	5.1	0	0	3
21:00	3	105.7	0	41.7	0	3.0	0	3.3	0	5.1	0	0	3
22:00	3	92.7	0	41.7	0	3.0	0	3.3	0	5.1	0	0	3
23:00	0	5.7	0	41.7	2	3.0	1	3.3	0	5.1	0	0	3
24:00	0	5.7	0	41.7	2	3.0	1	3.3	0	5.1	0	0	3

Key: *O*cuppancy, *E*quimpent * Profile for everyday except for the Plant room (no loads during weekends).

Table B.12: Definition of internal gains based on PHPP: profile 2 (3 persons, average $3.03\,\mathrm{W\,m^{-2}}$)*

Application	Base	Unit	Frequency		Quantity		kWh/ a	Wh/d	W/ h
Dishwasher	0.8	kWh/ use	87.0	$(p \cdot a)^{-1}$	3	p	215	587.67	24.49
Washing m.	0.7	kWh/ use	87.0	$(p \cdot a)^{-1}$	3	p	183	500.55	20.86
Dryer	2.1	kWh/ use	87.0	$(p \cdot a)^{-1}$	3	p	548	1501.64	62.57
Fridge	1.0	kWh/d	365.0	$d \cdot a^{-1}$	1	—	365	1000.00	41.67
Cooking	0.3	kWh/ use	730.0	$(p \cdot a)^{-1}$	3	p	548	1500.00	62.50
Lighting	60.0	W	2.9	$\mathrm{kh}(p \cdot a)^{-1}$	3	p	522	1430.14	59.59
Consumer e.	150.0	W	1.8	$\mathrm{kh}(p \cdot a)^{-1}$	3	p	788	2157.53	89.90
Other	50.0	kWh	1.0	$(p \cdot a)^{-1}$	3	p	150	410.96	17.12
Total	—		—		—			9088.49	378.69

* Figure based on average area of all cases.

B.6 Ventilation

Table B.13: Mechanical ventilation 1/2: Profile 1 (5p)

	FEES - Profile 1 (5p) [$\mathrm{L\,s^{-1}}$]						PH - Profile 1 (5p) [$\mathrm{L\,s^{-1}}$]					
Hour	LVL0	Bed. 1	Bed. 2	LVL2	LVL3	Total	LVL0	Bed. 1	Bed. 2	LVL2	LVL3	Total
01:00	13.2	8.0	4.0	12.0	11.7	37.0	6.8	16.7	8.3	25.0	16.7	48.5
02:00	13.2	8.0	4.0	12.0	11.7	37.0	6.8	16.7	8.3	25.0	16.7	48.5
03:00	13.2	8.0	4.0	12.0	11.7	37.0	6.8	16.7	8.3	25.0	16.7	48.5
04:00	13.2	8.0	4.0	12.0	11.7	37.0	6.8	16.7	8.3	25.0	16.7	48.5
05:00	13.2	8.0	4.0	12.0	11.7	37.0	6.8	16.7	8.3	25.0	16.7	48.5
06:00	13.2	8.0	4.0	12.0	11.7	37.0	6.8	16.7	8.3	25.0	16.7	48.5
07:00	13.2	5.3	5.8	11.0	11.7	36.0	16.7	8.3	8.3	16.7	8.3	41.7
08:00	20.0	5.3	5.8	11.0	11.7	42.8	41.7	2.9	3.2	6.1	6.1	53.8
09:00	13.2	5.3	5.8	11.0	11.7	36.0	6.8	2.9	3.2	6.1	6.1	19.0
10:00	13.2	5.3	5.8	11.0	11.7	36.0	6.8	2.9	3.2	6.1	6.1	19.0
11:00	13.2	5.3	5.8	11.0	11.7	36.0	6.8	2.9	3.2	6.1	6.1	19.0
12:00	13.2	5.3	5.8	11.0	11.7	36.0	6.8	2.9	3.2	6.1	6.1	19.0
13:00	13.2	5.3	5.8	11.0	11.7	36.0	6.8	2.9	3.2	6.1	6.1	19.0
14:00	13.2	5.3	5.8	11.0	11.7	36.0	6.8	2.9	3.2	6.1	6.1	19.0
15:00	13.2	5.3	5.8	11.0	11.7	36.0	6.8	2.9	3.2	6.1	6.1	19.0
16:00	13.2	5.3	5.8	11.0	11.7	36.0	6.8	2.9	3.2	6.1	6.1	19.0
17:00	13.2	5.3	5.8	11.0	30.0	54.3	25.0	2.9	5.4	8.3	8.3	41.7
18:00	60.0	5.3	5.8	11.0	30.0	101.0	25.0	2.9	5.4	8.3	8.3	41.7
19:00	60.0	5.3	5.8	11.0	30.0	101.0	25.0	2.9	5.4	8.3	8.3	41.7
20:00	13.2	5.3	5.8	11.0	11.7	36.0	25.0	2.9	5.4	8.3	8.3	41.7
21:00	20.0	5.3	5.8	11.0	11.7	42.8	41.7	2.9	3.2	6.1	6.1	53.8
22:00	20.0	5.3	5.8	11.0	11.7	42.8	41.7	2.9	3.2	6.1	6.1	53.8
23:00	13.2	8.0	4.0	12.0	11.7	37.0	6.8	16.7	8.3	25.0	16.7	48.5
24:00	13.2	8.0	4.0	12.0	11.7	37.0	6.8	16.7	8.3	25.0	16.7	48.5
Max.	60.0	8.0	5.8	12.0	30.0	101.0	41.7	16.7	8.3	25.0	16.7	53.8

Table B.14: Mechanical ventilation 2/2: Profile 2 (3p)

	FEES - Profile 2 (3p) [$\mathrm{L\,s^{-1}}$]						PH - Profile 2 (3p) [$\mathrm{L\,s^{-1}}$]					
Hour	LVL0	Bed. 1	Bed. 2	LVL2	LVL3	Total	LVL0	Bed. 1	Bed. 2	LVL2	LVL3	Total
01:00	13.2	8.0	4.0	12.0	11.7	37.0	7.2	16.7	8.3	25.0	6.4	38.6
02:00	13.2	8.0	4.0	12.0	11.7	37.0	7.2	16.7	8.3	25.0	6.4	38.6
03:00	13.2	8.0	4.0	12.0	11.7	37.0	7.2	16.7	8.3	25.0	6.4	38.6
04:00	13.2	8.0	4.0	12.0	11.7	37.0	7.2	16.7	8.3	25.0	6.4	38.6
05:00	13.2	8.0	4.0	12.0	11.7	37.0	7.2	16.7	8.3	25.0	6.4	38.6
06:00	13.2	8.0	4.0	12.0	11.7	37.0	7.2	16.7	8.3	25.0	6.4	38.6
07:00	13.2	5.3	5.8	11.0	11.7	36.0	8.3	8.3	8.3	16.7	6.4	31.4
08:00	13.2	5.3	5.8	11.0	11.7	36.0	25.0	3.1	3.3	6.4	6.4	37.8
09:00	13.2	5.3	5.8	11.0	30.0	54.3	16.7	3.1	3.3	6.4	8.3	31.4
10:00	13.2	5.3	5.8	11.0	30.0	54.3	16.7	3.1	3.3	6.4	8.3	31.4
11:00	60.0	5.3	5.8	11.0	30.0	101.0	16.7	3.1	3.3	6.4	8.3	31.4
12:00	13.2	5.3	5.8	11.0	11.7	36.0	25.0	3.1	3.3	6.4	6.4	37.8
13:00	13.2	5.3	5.8	11.0	11.7	36.0	16.7	3.1	3.3	6.4	8.3	31.4
14:00	13.2	5.3	5.8	11.0	11.7	36.0	16.7	3.1	3.3	6.4	8.3	31.4
15:00	13.2	5.3	5.8	11.0	11.7	36.0	16.7	3.1	3.3	6.4	8.3	31.4
16:00	13.2	5.3	5.8	11.0	11.7	36.0	16.7	3.1	3.3	6.4	8.3	31.4
17:00	13.2	5.3	5.8	11.0	11.7	36.0	16.7	3.1	3.3	6.4	8.3	31.4
18:00	60.0	5.3	5.8	11.0	11.7	82.8	25.0	3.1	3.3	6.4	6.4	37.8
19:00	13.2	5.3	5.8	11.0	11.7	36.0	25.0	3.1	3.3	6.4	6.4	37.8
20:00	13.2	5.3	5.8	11.0	11.7	36.0	25.0	3.1	3.3	6.4	6.4	37.8
21:00	13.2	5.3	5.8	11.0	11.7	36.0	25.0	3.1	3.3	6.4	6.4	37.8
22:00	13.2	5.3	5.8	11.0	11.7	36.0	25.0	3.1	3.3	6.4	6.4	37.8
23:00	13.2	8.0	4.0	12.0	11.7	37.0	7.2	16.7	8.3	25.0	6.4	38.6
24:00	13.2	8.0	4.0	12.0	11.7	37.0	7.2	16.7	8.3	25.0	6.4	38.6
Max.	60.0	8.0	5.8	12.0	30.0	101.0	25.0	16.7	8.3	25.0	8.3	38.6

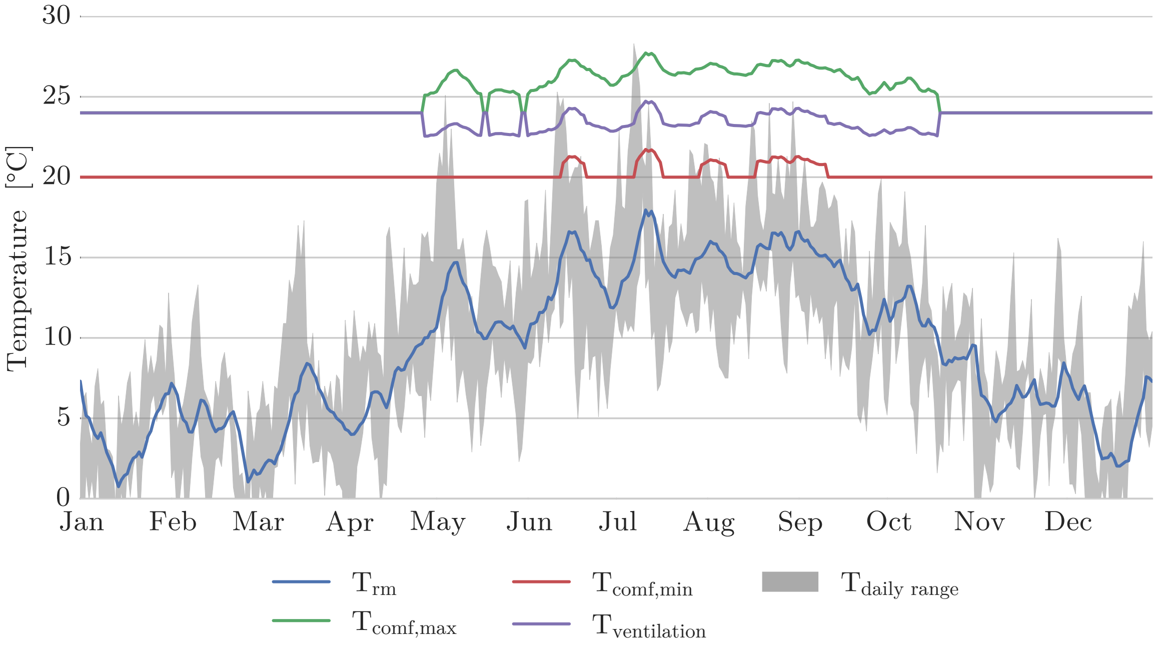


Figure B.1: Manchester purge ventilation temperature trigger: Day

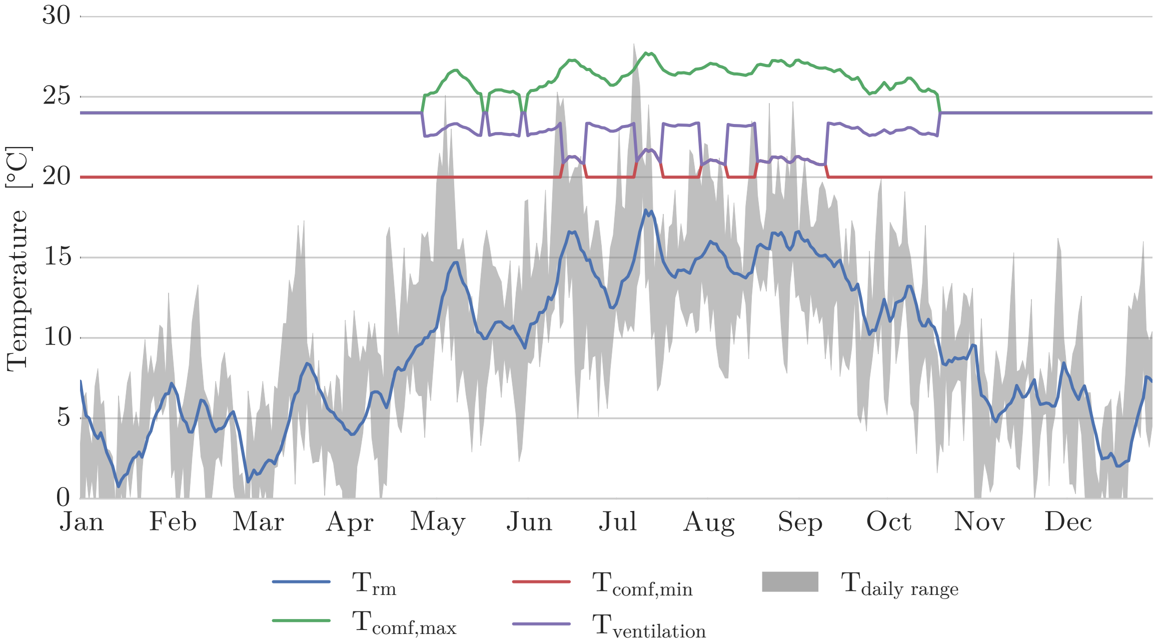


Figure B.2: Manchester purge ventilation temperature trigger: Night

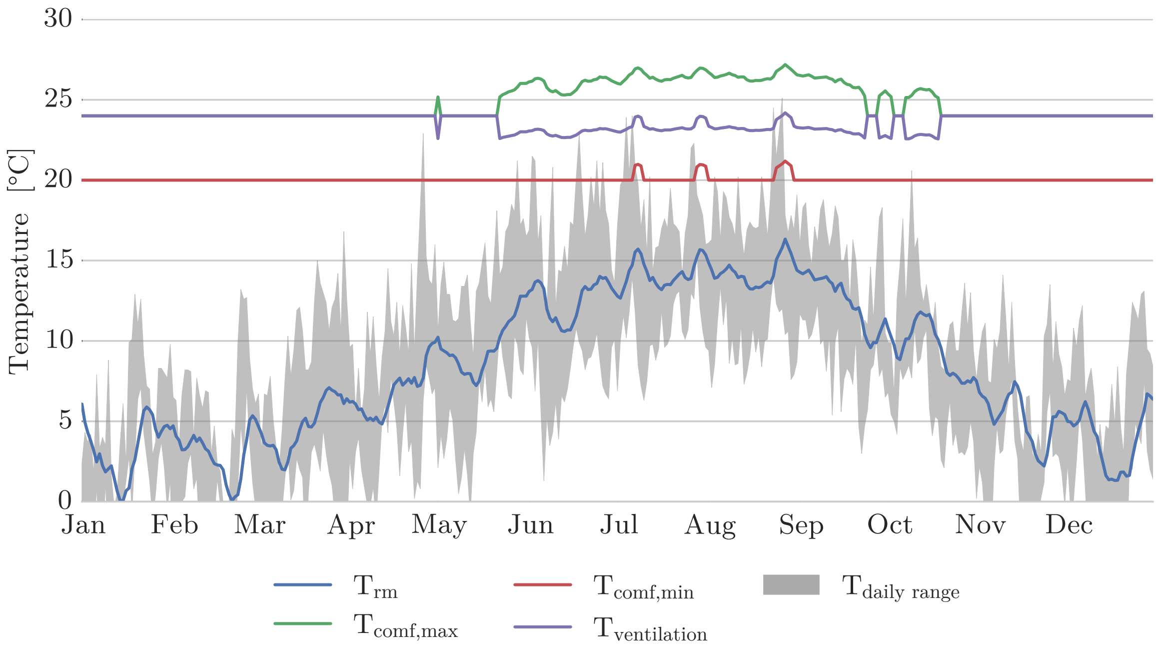


Figure B.3: Edinburgh purge ventilation temperature trigger: Day

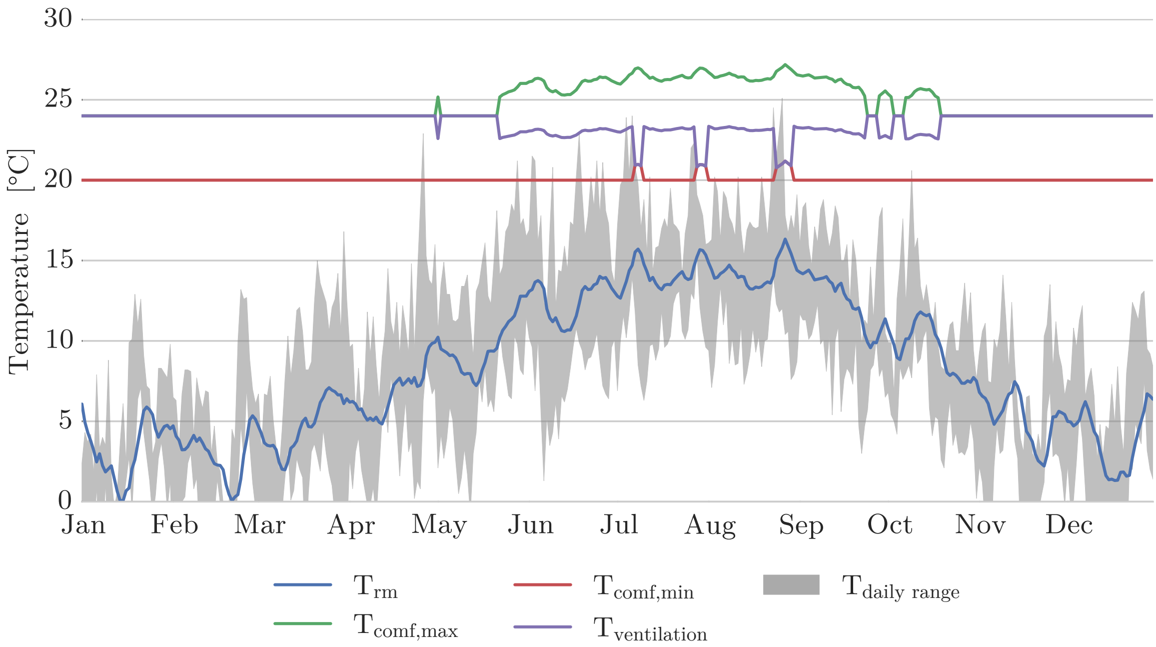


Figure B.4: Edinburgh purge ventilation temperature trigger: Night

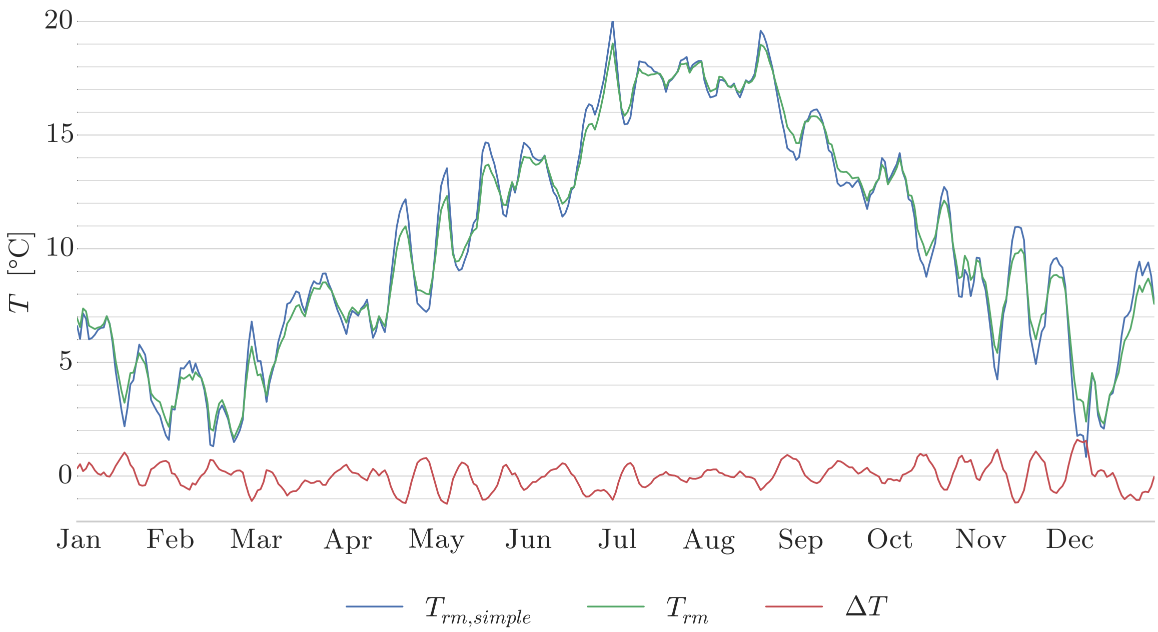
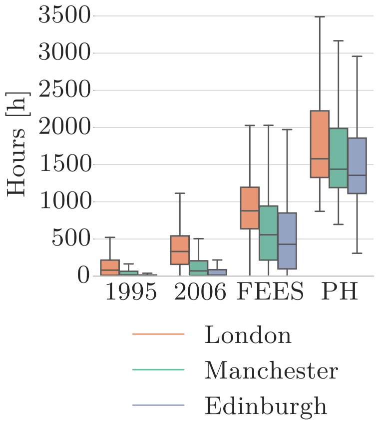


Figure B.5: London: Running mean versus its simplified formulation

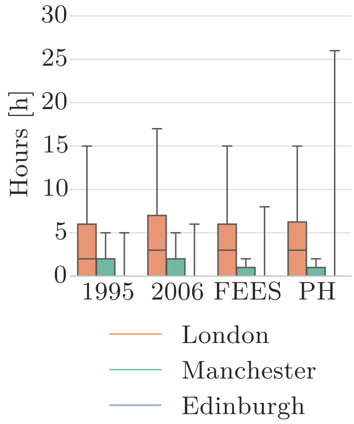
APPENDIX C

Extended output

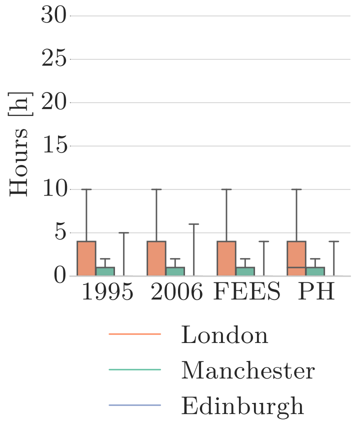
C.1 Current weather



(a) Purge: None



(b) Purge: Day



(c) Purge: Night

Figure C.1: Duration (indicator 1-1): Data distribution (Note: Y axis scale adapted for *Purge: None*)

	1995		2006		FEES		PH	
μ	53.01	±4.54	139.09	±9.03	636.01	±26.12	1603.47	±27.88
σ	87.96	±3.21	174.76	±6.38	505.65	±18.47	539.70	±19.71

(a) Purge: None

	1995		2006		FEES		PH	
μ	1.03	±0.10	1.24	±0.10	0.82	±0.08	0.85	±0.08
σ	1.84	±0.07	1.98	±0.07	1.58	±0.06	1.62	±0.06

(b) Purge: Day

	1995		2006		FEES		PH	
μ	0.85	±0.09	0.99	±0.09	0.60	±0.07	0.57	±0.06
σ	1.65	±0.06	1.74	±0.06	1.27	±0.05	1.24	±0.05

(c) Purge: Night

Table C.1: Duration (indicator 1-1): Manchester average hours above ACM $T_{cm,max}$ (CI:95%)

	1995		2006		FEES		PH	
μ	23.19	±3.06	74.84	±6.70	530.30	±25.06	1506.84	±26.98
σ	59.28	±2.16	129.73	±4.74	485.20	±17.72	522.44	±19.08

(a) Purge: None

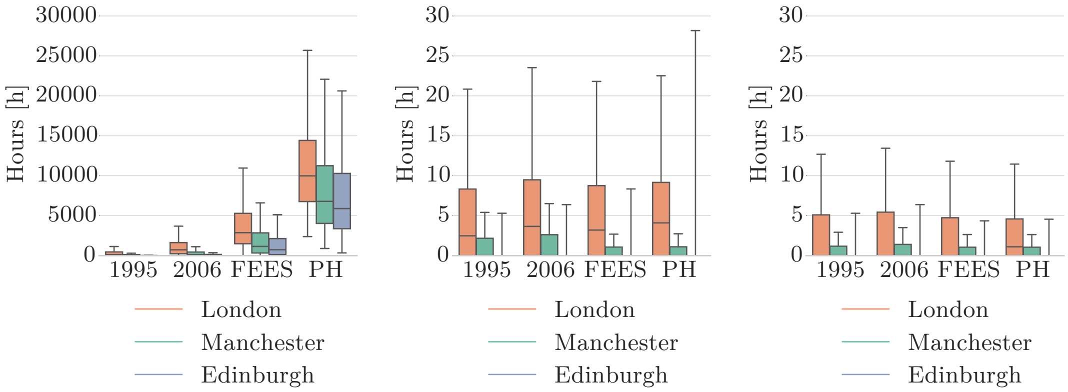
	1995		2006		FEES		PH	
μ	0.08	±0.02	0.10	±0.02	0.21	±0.03	0.65	±0.12
σ	0.39	±0.01	0.43	±0.02	0.60	±0.02	2.30	±0.08

(b) Purge: Day

	1995		2006		FEES		PH	
μ	0.08	±0.02	0.10	±0.02	0.20	±0.03	0.23	±0.03
σ	0.39	±0.01	0.43	±0.02	0.55	±0.02	0.59	±0.02

(c) Purge: Night

Table C.2: Duration (indicator 1-1): Edinburgh average hours above ACM $T_{cm,max}$ (CI:95%)



(a) Purge: None (b) Purge: Day (c) Purge: Night

Figure C.2: Discomfort (indicator 1-3): Data distribution (Note: Y axis scale adapted for *Purge: None*)

	1995		2006		FEES		PH	
μ	130.33	±14.41	373.62	±32.05	1926.53	±111.08	8151.44	±276.05
σ	278.91	±10.19	620.58	±22.66	2150.56	±78.54	5344.72	±195.20

(a) Purge: None

	1995		2006		FEES		PH	
μ	1.35	±0.13	1.63	±0.14	1.04	±0.11	1.08	±0.11
σ	2.52	±0.09	2.70	±0.10	2.09	±0.08	2.13	±0.08

(b) Purge: Day

	1995		2006		FEES		PH	
μ	1.14	±0.12	1.32	±0.12	0.78	±0.09	0.75	±0.09
σ	2.29	±0.08	2.41	±0.09	1.73	±0.06	1.69	±0.06

(c) Purge: Night

Table C.3: Discomfort (indicator 1-3): Manchester average PPD-weighted hours above ACM $T_{cm,max}$ (CI:95%)

	1995		2006		FEES		PH	
μ	48.07	±7.80	169.12	±19.50	1470.54	±96.06	7298.28	±264.71
σ	151.05	±5.52	377.63	±13.79	1859.86	±67.93	5125.13	±187.18

(a) Purge: None

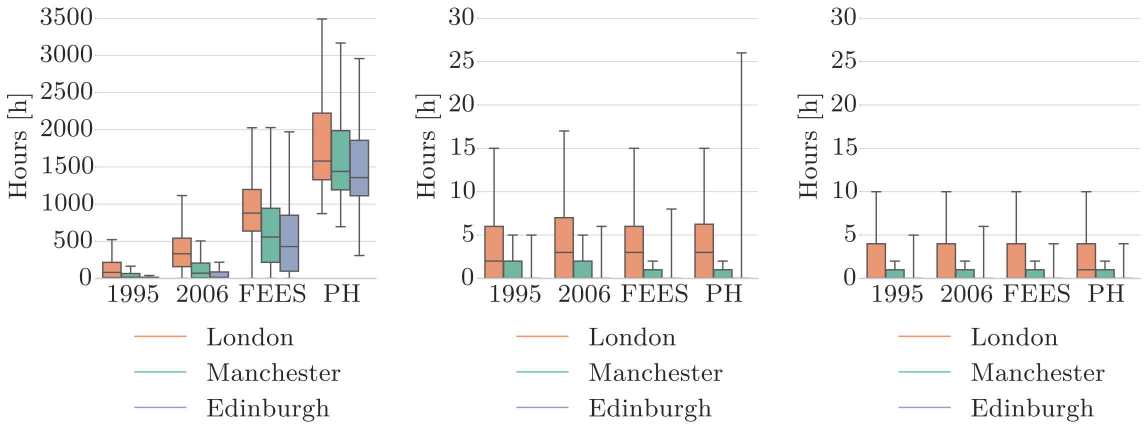
	1995		2006		FEES		PH	
μ	0.09	±0.02	0.10	±0.02	0.22	±0.03	0.69	±0.13
σ	0.41	±0.02	0.46	±0.02	0.63	±0.02	2.49	±0.09

(b) Purge: Day

	1995		2006		FEES		PH	
μ	0.09	±0.02	0.10	±0.02	0.21	±0.03	0.25	±0.03
σ	0.41	±0.02	0.46	±0.02	0.57	±0.02	0.62	±0.02

(c) Purge: Night

Table C.4: Discomfort (indicator 1-3): Edinburgh average PPD-weighted hours above ACM $T_{cm,max}$ (CI:95%)



(a) Purge: None (b) Purge: Day (c) Purge: Night

Figure C.3: Cooling energy demand (indicator 3): Data distribution (Note: Y axis scale adapted for *Purge: None*)

	1995		2006		FEES		PH	
μ	25.24	±1.77	72.78	±3.41	198.20	±6.44	468.40	±11.36
σ	34.23	±1.25	65.96	±2.41	124.60	±4.55	219.98	±8.03

(a) Purge: None

	1995		2006		FEES		PH	
μ	0.51	±0.04	0.59	±0.04	0.49	±0.03	0.47	±0.03
σ	0.72	±0.03	0.78	±0.03	0.67	±0.02	0.65	±0.02

(b) Purge: Day

	1995		2006		FEES		PH	
μ	0.29	±0.03	0.29	±0.03	0.20	±0.02	0.16	±0.02
σ	0.58	±0.02	0.59	±0.02	0.44	±0.02	0.39	±0.01

(c) Purge: Night

Table C.5: Discomfort (indicator 3): London average CDH for 25 °C when above ACM $T_{cm,max}$ (CI:95%)

	1995		2006		FEES		PH	
μ	7.78	±0.73	21.30	±1.56	100.59	±4.97	339.55	±9.47
σ	14.22	±0.52	30.27	±1.11	96.20	±3.51	183.27	±6.69

(a) Purge: None

	1995		2006		FEES		PH	
μ	0.10	±0.01	0.12	±0.01	0.08	±0.01	0.08	±0.01
σ	0.19	±0.01	0.20	±0.01	0.16	±0.01	0.16	±0.01

(b) Purge: Day

	1995		2006		FEES		PH	
μ	0.08	±0.01	0.10	±0.01	0.06	±0.01	0.05	±0.01
σ	0.17	±0.01	0.18	±0.01	0.13	0.00	0.12	0.00

(c) Purge: Night

Table C.6: Discomfort (indicator 3): Manchester average CDH for 25 °C when above ACM $T_{cm,max}$ (CI:95%)

	1995		2006		FEES		PH	
μ	2.39	±0.36	8.45	±0.87	69.81	±4.05	283.70	±8.68
σ	6.91	±0.25	16.87	±0.62	78.38	±2.86	168.05	±6.14

(a) Purge: None

	1995		2006		FEES		PH	
μ	–	–	–	–	–	–	–	–
σ	–	–	–	–	–	–	–	–

(b) Purge: Day

	1995		2006		FEES		PH	
μ	–	–	–	–	–	–	–	–
σ	–	–	–	–	–	–	–	–

(c) Purge: Night

Table C.7: Discomfort (indicator 3): Edinburgh average CDH for 25 °C when above ACM $T_{cm,max}$ (CI:95%)

C.2 Future weather

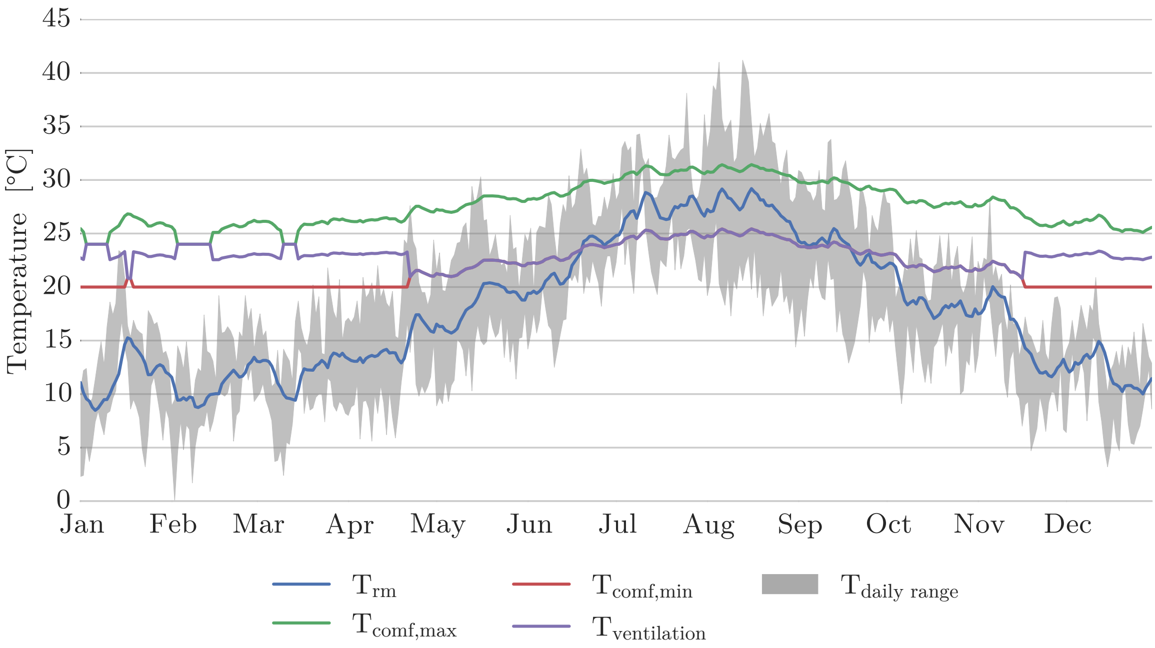
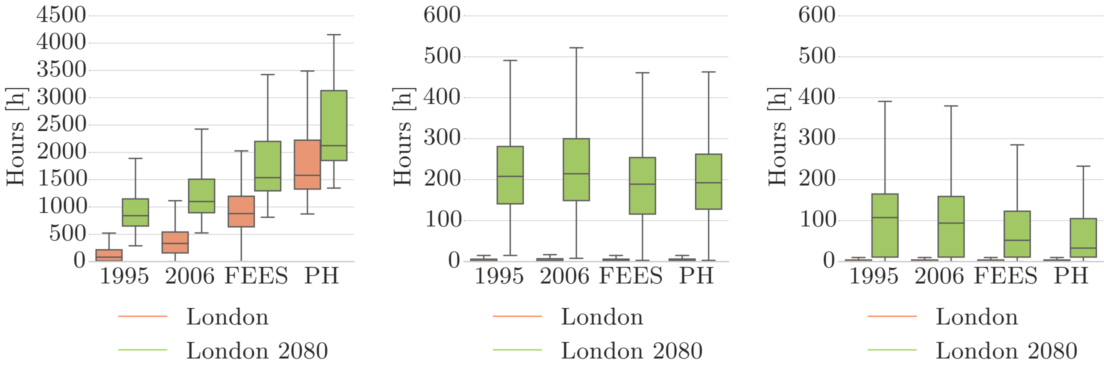


Figure C.4: London 2080 (TRY, High emissions, 90% probability) purge ventilation temperature trigger: Night



(a) Purge: None (b) Purge: Day (c) Purge: Night

Figure C.5: Duration (indicator 1-1): Data distribution for future weather (Note: London 2080 (TRY, High emissions, 90% probability), Y axis scale adapted for *Purge: None*)

	1995		2006		FEES		PH	
μ	933.85	±19.95	1226.97	±22.43	1730.29	±29.49	2373.15	±36.86
σ	386.19	±14.10	434.27	±15.86	570.95	±20.85	713.61	±26.06

(a) Purge: None

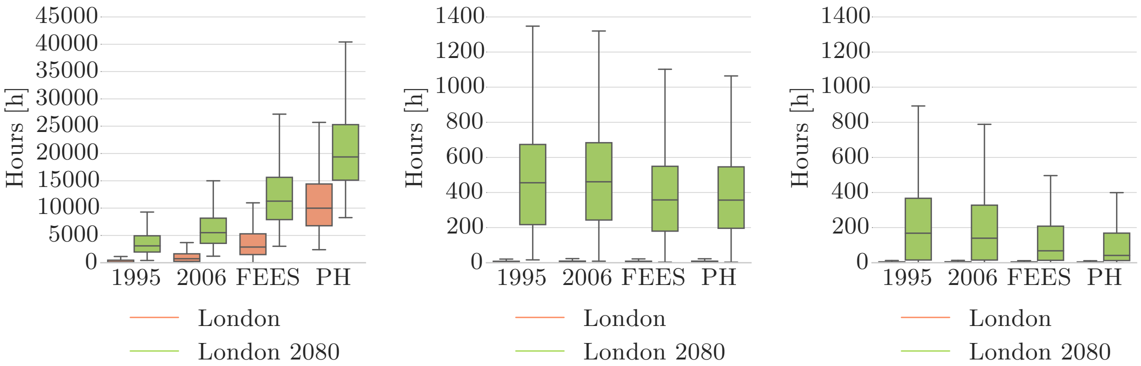
	1995		2006		FEES		PH	
μ	216.63	±6.00	230.06	±6.26	197.16	±5.81	204.92	±5.95
σ	116.25	±4.25	121.11	±4.42	112.55	±4.11	115.23	±4.21

(b) Purge: Day

	1995		2006		FEES		PH	
μ	109.31	±4.81	101.99	±4.71	73.44	±3.92	63.46	±3.66
σ	93.16	±3.40	91.25	±3.33	75.81	±2.77	70.93	±2.59

(c) Purge: Night

Table C.8: Duration (indicator 1-1): London 2080 (TRY, High emissions, 90% probability) average hours above ACM $T_{cm,max}$ (CI:95%)



(a) Purge: None (b) Purge: Day (c) Purge: Night

Figure C.6: Discomfort (indicator 1-3): Data distribution for future weather (Notes: London 2080 (TRY, High emissions, 90% probability), Y axis scale adapted for *Purge: None*)

	1995		2006		FEES		PH	
μ	3772.69	±131.36	6371.63	±192.70	12 434.78	±312.20	21 088.34	±401.74
σ	2543.33	±92.89	3730.98	±136.26	6044.58	±220.76	7778.17	±284.07

(a) Purge: None

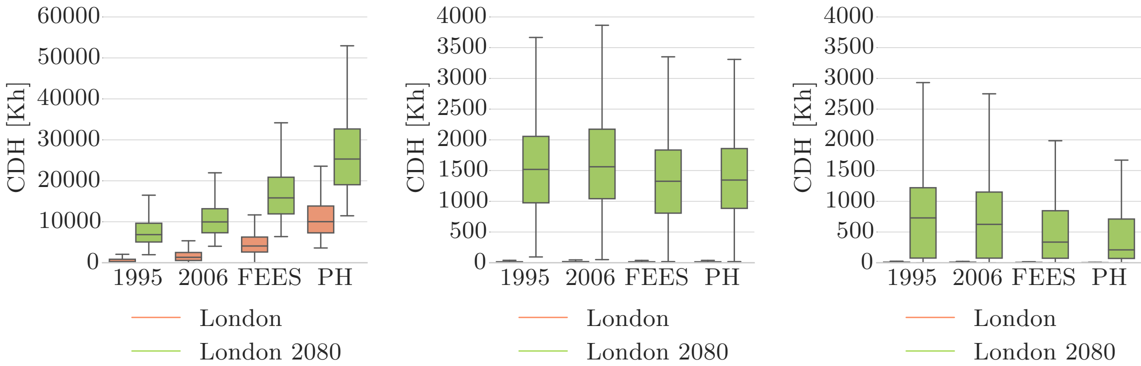
	1995		2006		FEES		PH	
μ	481.14	±16.19	497.98	±16.39	394.38	±14.01	397.40	±13.85
σ	313.41	±11.45	317.33	±11.59	271.33	±9.91	268.10	±9.79

(b) Purge: Day

	1995		2006		FEES		PH	
μ	238.87	±13.25	214.91	±12.58	138.94	±9.28	116.20	±8.39
σ	256.60	±9.37	243.51	±8.89	179.59	±6.56	162.45	±5.93

(c) Purge: Night

Table C.9: Discomfort (indicator 1-3): London 2080 (TRY, High emissions, 90% probability) average PPD-weighted hours above ACM $T_{cm,max}$ (CI:95%)



(a) Purge: None (b) Purge: Day (c) Purge: Night

Figure C.7: Cooling energy demand (indicator 3): Data distribution for future weather (Notes: London 2080 (TRY, High emissions, 90% probability), Y axis scale adapted for *Purge: None*)

	1995		2006		FEES		PH	
μ	321.39	±7.79	454.14	±9.81	717.36	±14.85	1131.50	±22.29
σ	150.86	±5.51	189.99	±6.94	287.47	±10.50	431.48	±15.76

(a) Purge: None

	1995		2006		FEES		PH	
μ	65.92	±1.87	69.52	±1.93	58.42	±1.76	60.27	±1.79
σ	36.24	±1.32	37.46	±1.37	34.14	±1.25	34.66	±1.27

(b) Purge: Day

	1995		2006		FEES		PH	
μ	32.89	±1.51	30.38	±1.47	21.32	±1.19	18.24	±1.10
σ	29.28	±1.07	28.43	±1.04	22.99	±0.84	21.32	±0.78

(c) Purge: Night

Table C.10: Discomfort (indicator 3): London 2080 (TRY, High emissions, 90% probability) average CDH for 25 °C when above ACM $T_{cm,max}$ (CI:95%)